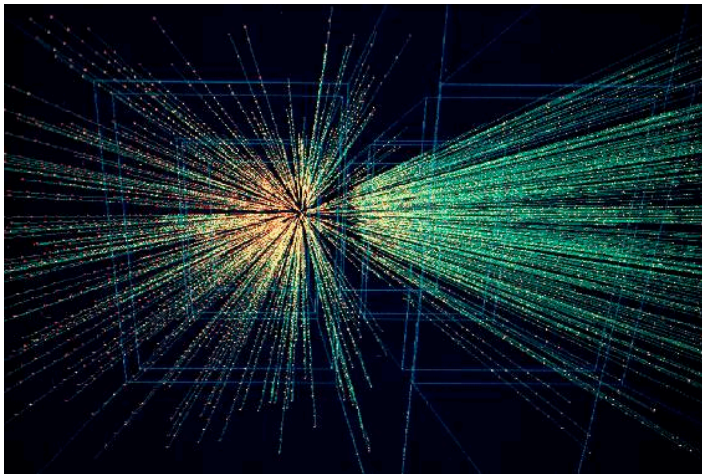
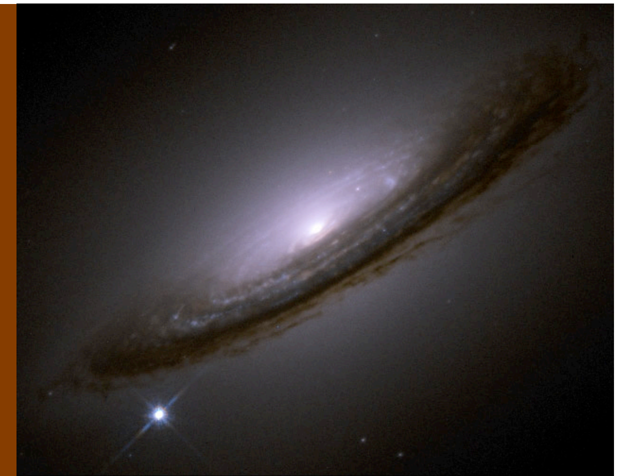
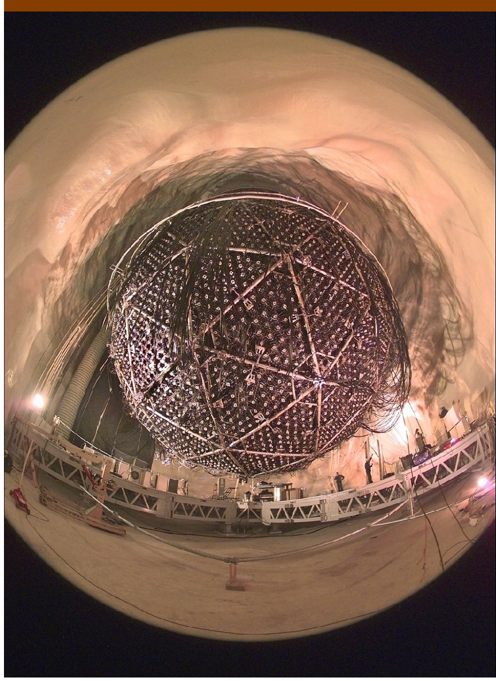




Connecting Quarks with the Cosmos: Notes from the Underground

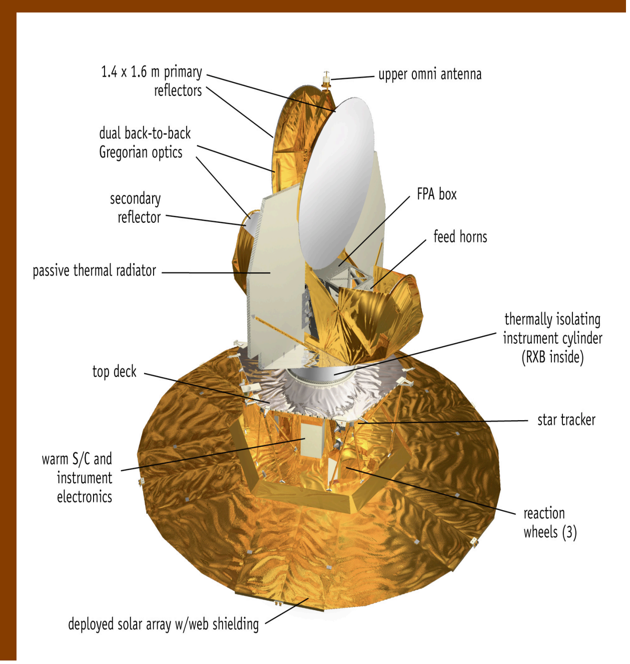


Kevin Lesko

Institute for Nuclear and Particle Astrophysics

Berkeley Lab

DNP 30 October, 2003



Connecting Quarks with the Cosmos:

Eleven Science Questions for the New Century

Notes from the Underground

- Briefly - what is the study about,
  what are the questions?
  - Science in the Cracks and Fissures
- What are the connections to Underground Science, in general, and to Nuclear Physics, in particular?
  - Recent Progress and Experiments
  - What Physics Areas would Benefit from an Underground Laboratory?

Committee on the Physics of the Universe

- Charge by the National Research Council Board on Physics and Astronomy:

  Prepare an assessment and strategy for research at the intersection of astronomy and physics.

Kevin Lesko

Notes from the Underground

- To begin to act, you know, you must first have your mind completely at ease and without a trace of doubt left in it. Well, how am I, for example, to set my mind at rest? Where are the primary causes on which I am to build? Where are my bases? Where am I to get them from? I exercise myself in the process of thinking, and consequently with me every primary cause at once draws after itself another still more primary, and so on to infinity. That is precisely the essence of every sort of consciousness and thinking. It must be a case of the laws of nature again.

  Fyodor **Dostoevsky**, *Notes from the Underground*

Quarks *to* the Cosmos: National Academy Report

1. What is the Dark Matter?

2. What are the masses of the Neutrinos, and how have they shaped the evolution of the universe?
3. Are there additional space-time dimensions?
4. What is the nature of the dark energy?

5. Are Protons unstable?
6. How did the Universe begin?
7. Did Einstein have the last word on Gravity?

Quarks to the Cosmos

8. How do cosmic accelerators work and what are they accelerating?
9. Are there new states of matter at exceedingly high temperature and density?
10. Is a new theory of matter and light needed at the highest energies?

11. How were the elements from Iron to Uranium made?

~ half are conducted with or intimately linked to underground laboratories

Why Go Underground? How Deep?

Small Expts,
High Thresholds,
Prototyping,
Manufacturing

Supernovae
Security
High Energy

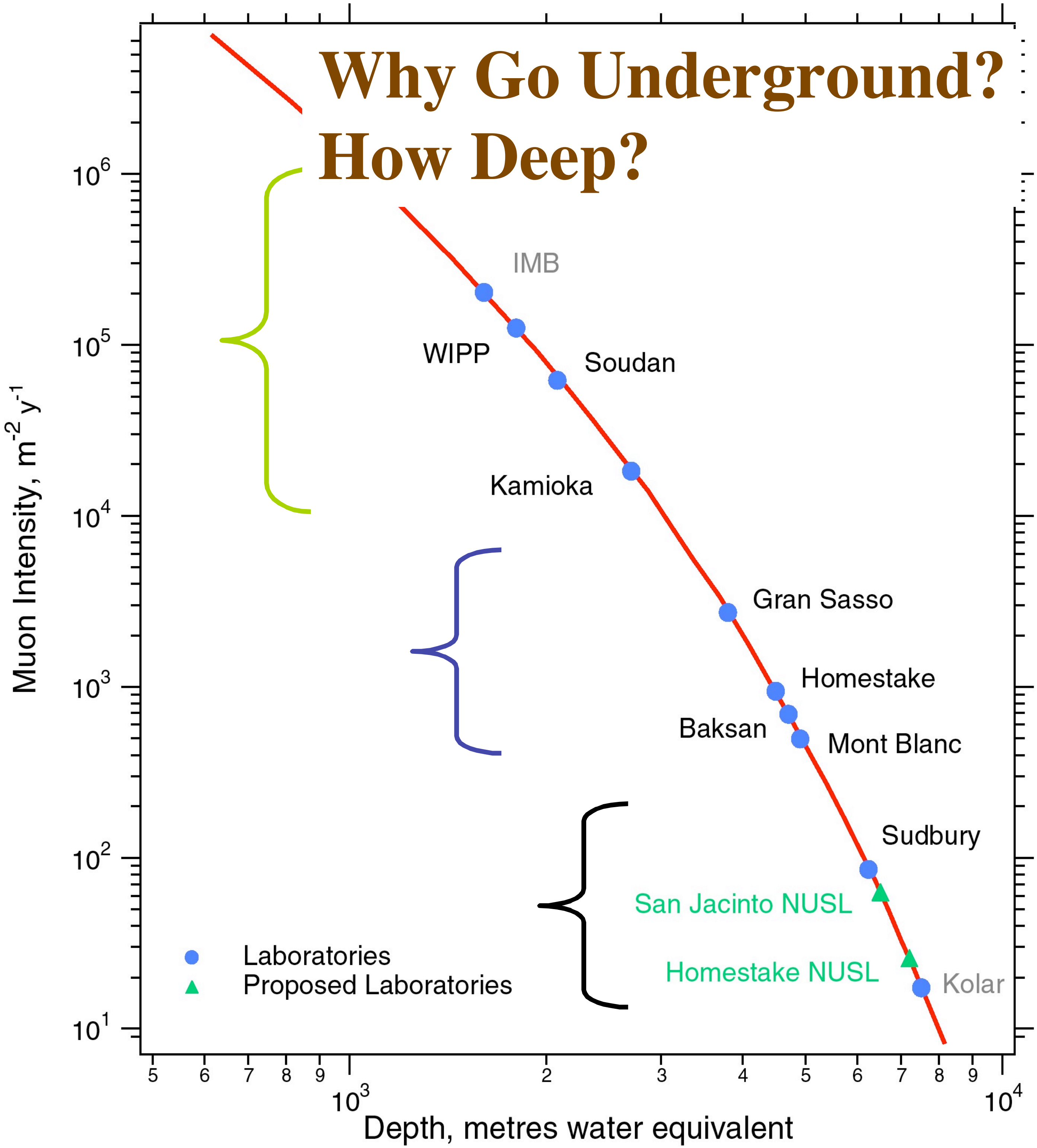
Medium-Large,
Lower Thresholds

Large Multi-purpose Expts

Large Scale Expts,
Lowest Thresholds

Dark Matter, Solar-□, 0-□ □□ decay

Kevin Lesko



What is the Dark Matter?

- Compelling evidence for DM
  - Spiral Galaxy Rotational Curves
  - Galactic Cluster Velocities
  - Gravitational Lensing
  - "Great Attractor" evidence within Large Clusters
  - CMBR Large Scale Structure

$\Omega_C = 35\%$

- Types of DM
  - Dark Baryons
    - Big Bang Nucleosynthesis
    - CMB Structure
    - Quasar Light Absorption by Gas Clouds
    - Counting Stars
  - Exotic Dark Matter

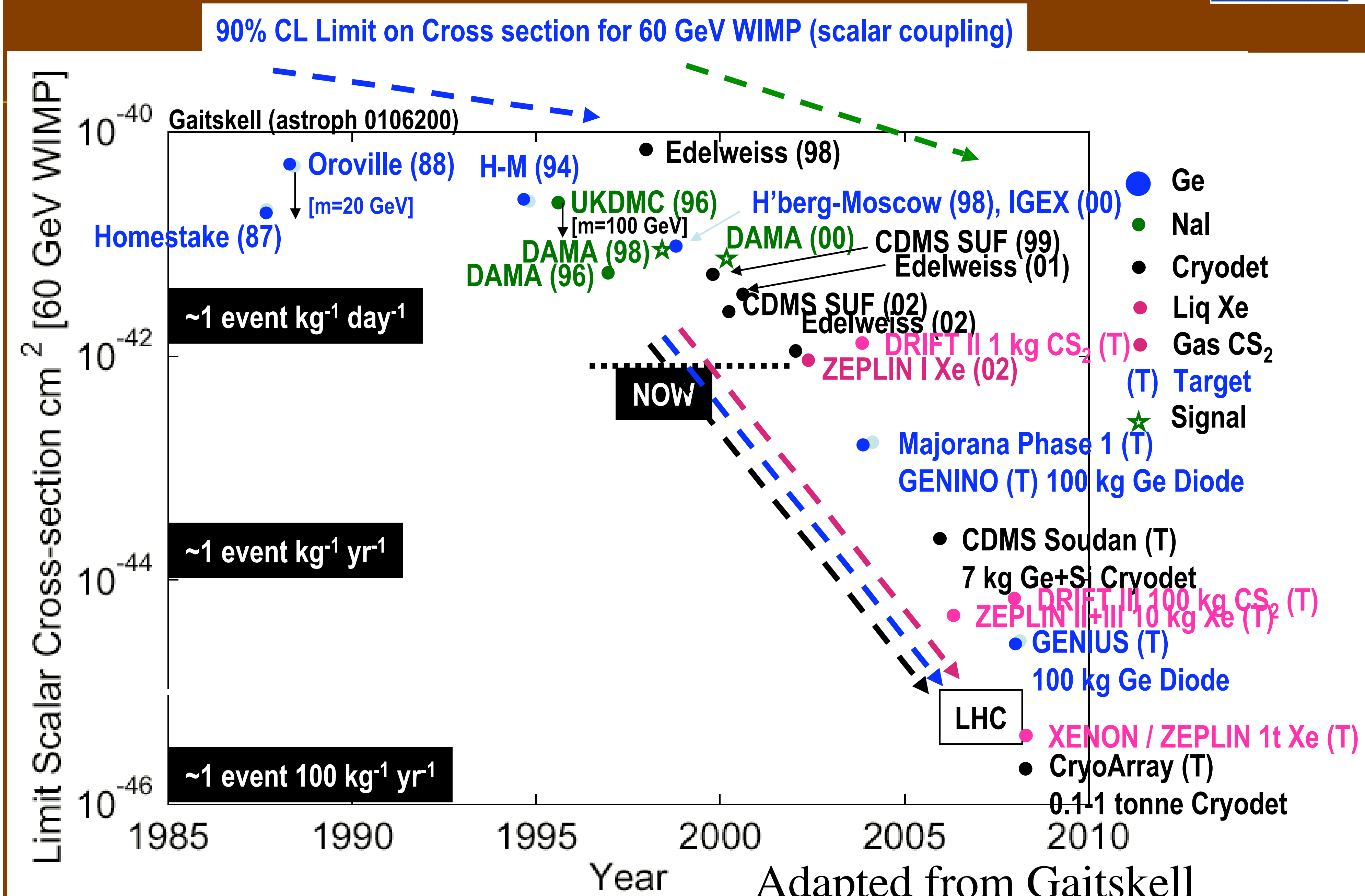
$\Omega_{baryon} = 4\%$

$\Omega_{baryon} = 1.3\%$

$\Omega_{exotic} = \sim 30\%$

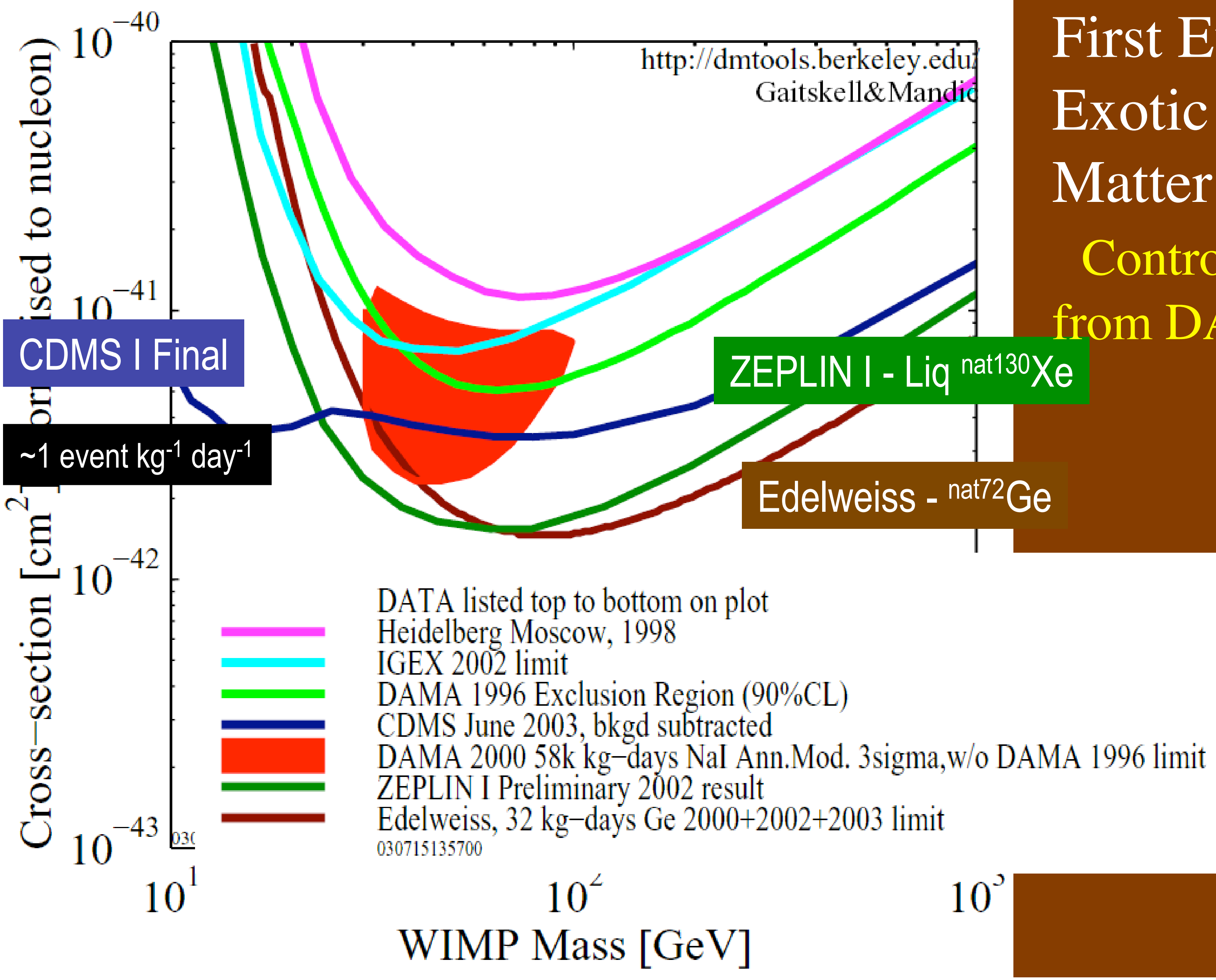
Neutrinos are the first source of DM!

DM: Direct Detection: History & Future



Adapted from Gaitskell

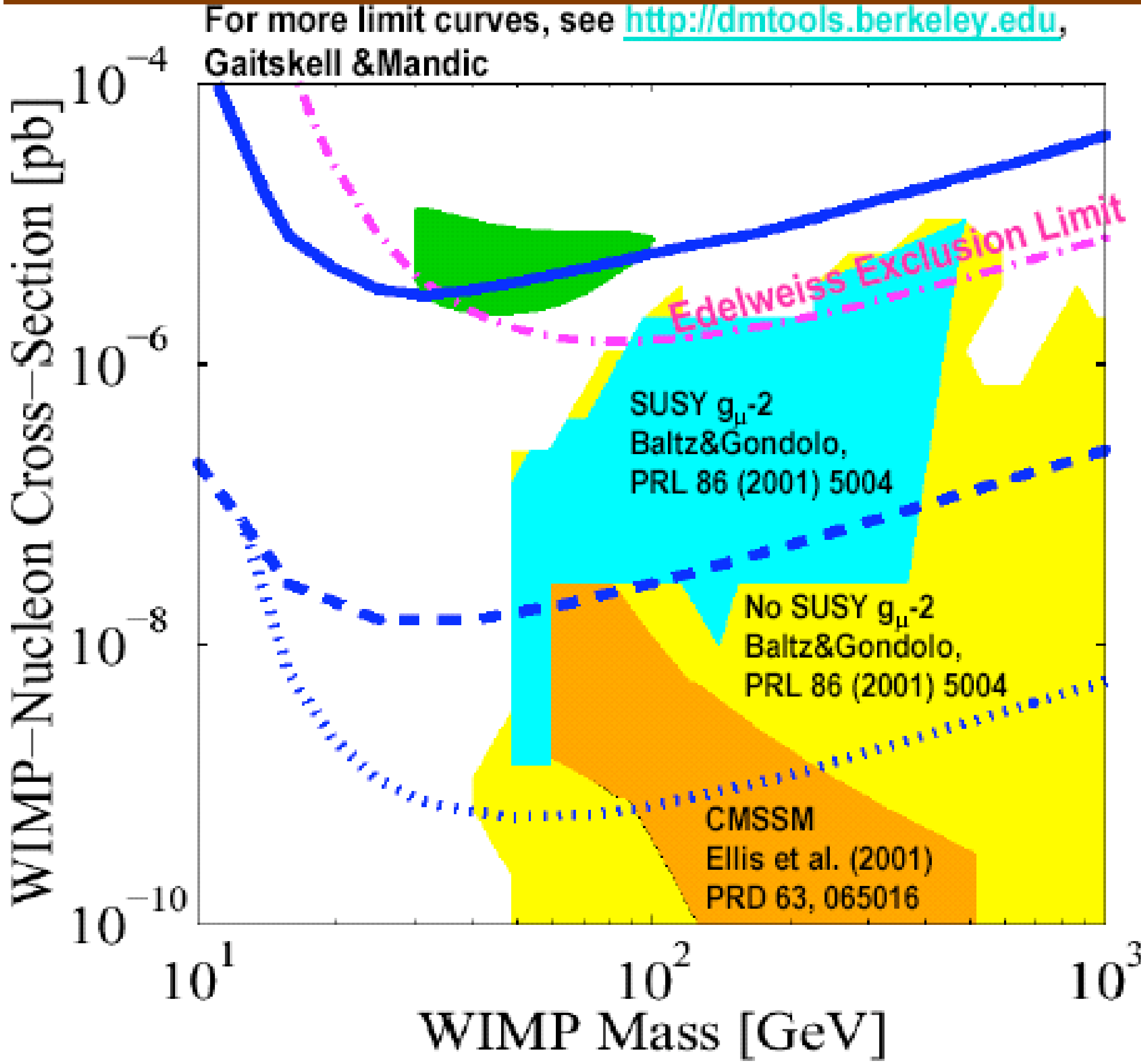
More Recently…



First Evidence of Exotic Dark Matter?

Controversial Reports from DAMA

Dark Matter Sensitivity



Limit from CDMS 1999 Ge BLIP run at Stanford

Projected sensitivity for CDMS at Soudan, with 7 towers >5 kg Ge, >2 kg Si: 0.0003 events/kg/keV/day (100x better than present limit at Stanford).

Projected sensitivity for a 1-ton CryoArray (~ 1 event / (100 kg yr)

Neutrino Physics (ν masses and affects on evolution of the Universe)

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

Maki-Nakagawa-Sakata-Pontecorvo

- Neutrino Masses & Neutrino Mixing
- Neutrinoless ββ decay
- Solar Neutrinos
- Atmospheric Neutrinos
- Long Base Line Experiments & Reactor Experiments
- Supernovae
- Potential CP violation and Leptogenesis

$$\begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix} \begin{pmatrix} \cos\theta_{13} & 0 & e^{-i\delta_{CP}}\sin\theta_{13} \\ 0 & 1 & 0 \\ -e^{i\delta_{CP}}\sin\theta_{13} & 0 & \cos\theta_{13} \end{pmatrix} \begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{i\alpha/2} & 0 \\ 0 & 0 & e^{i\alpha/2+i\beta} \end{pmatrix}$$

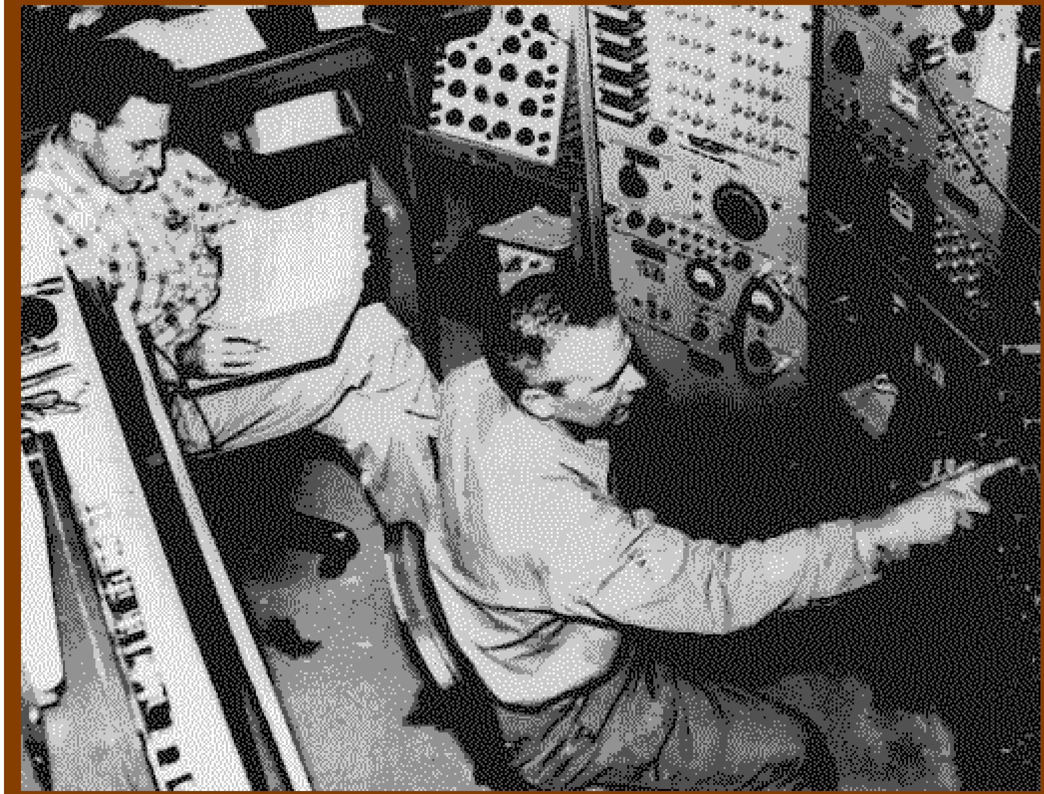
Neutrino Physics History

- "The neutrino is the smallest bit of material reality ever conceived of by man: the largest is the universe. To attempt to understand something of one in terms of the other is to attempt to span the dimension in which lie all manifestations of natural law. Yet even now, despite our shadowy knowledge of these limits, problems arise to try the imagination in such an attempt."

  F. Reines and C.L. Cowan, Jr. Nature, 1956, **178**, 446-449

Neutrino Physics - Reactor

Discovery of the Neutrino



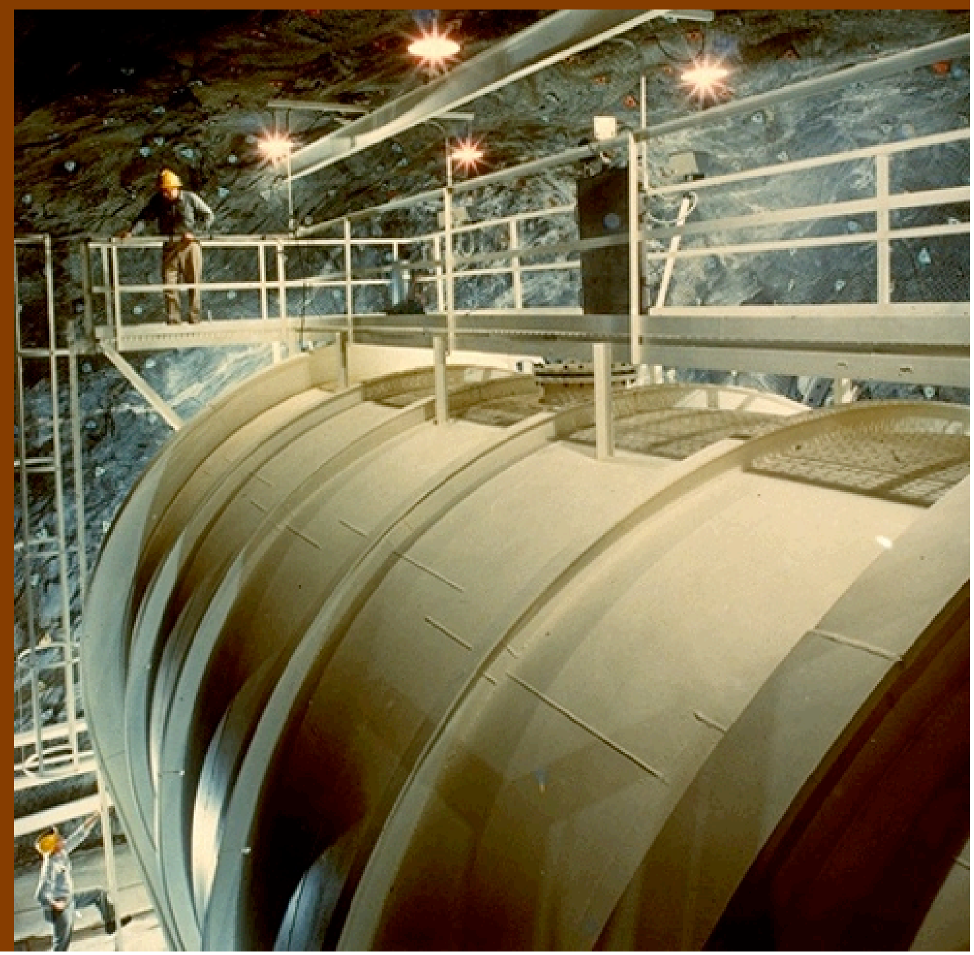
Nobel 1995 "for pioneering experimental contributions to lepton physics, specifically for the detection of the neutrino" Fred Reines

"Detection of the **Free Neutrino**: A Confirmation" Cowan *et al.* Science, 1956, **124**, 103-104

Neutrino Physics - Solar

Solar Neutrino Problem - not enough neutrinos

Nobel 2002: "for pioneering contributions to astrophysics, in particular for the detection of cosmic neutrinos" Ray Davis

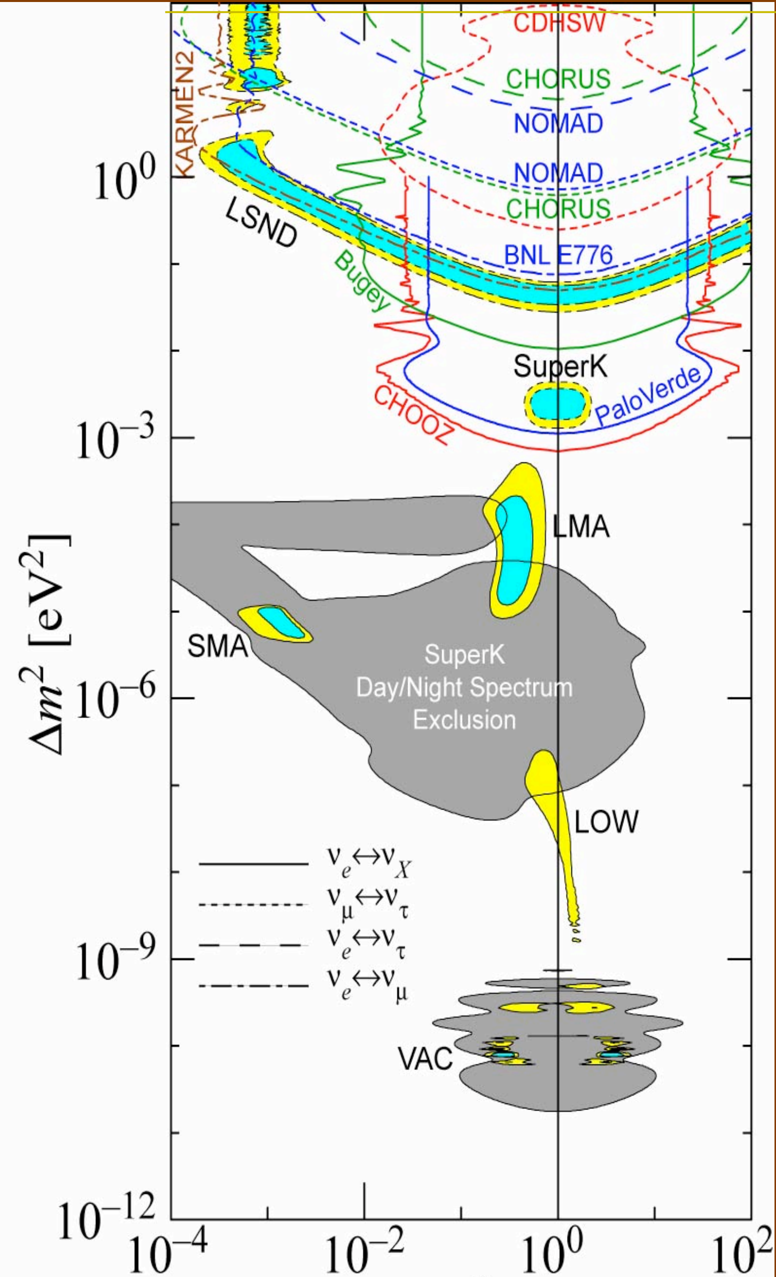


Neutrino Physics - Atmospheric

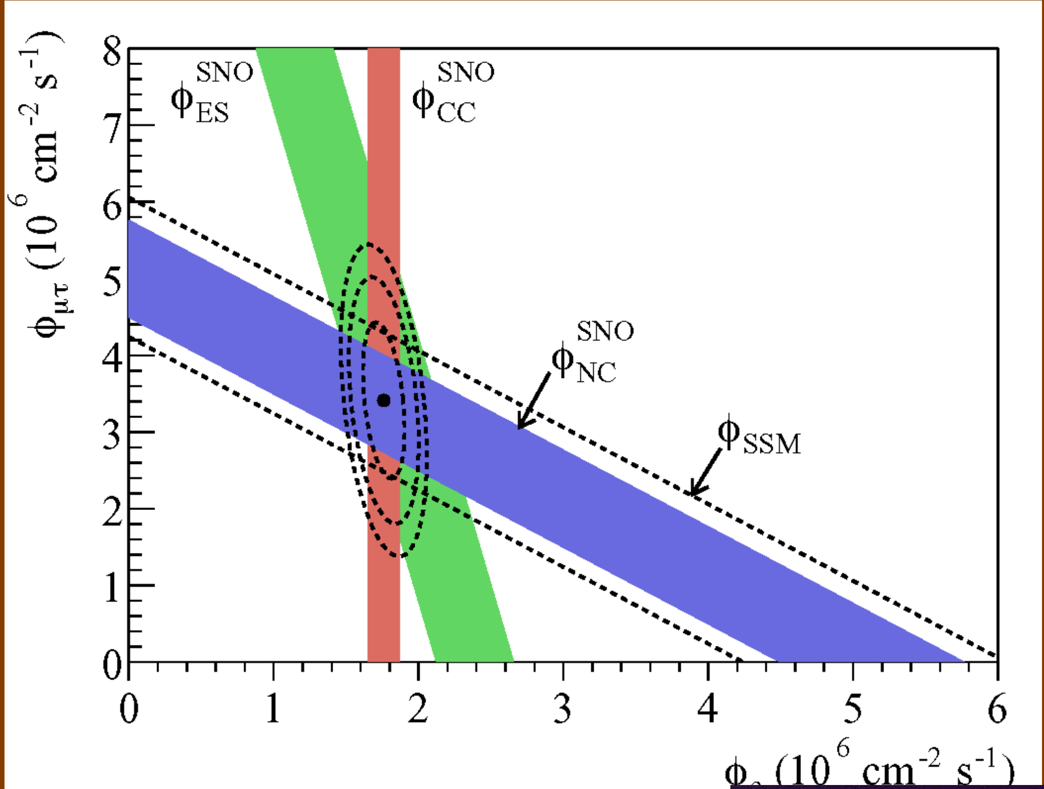
Real-time Detection and Supernova Neutrino

Nobel 2002 "for pioneering contributions to astrophysics, in particular for the detection of cosmic neutrinos" Koshiba-sensei

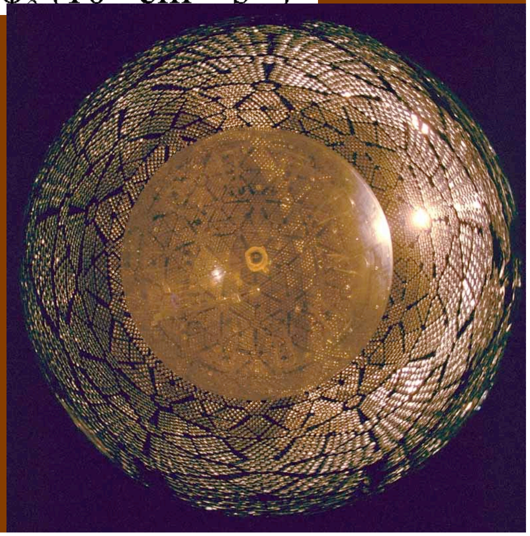
Neutrino Physics - Solar



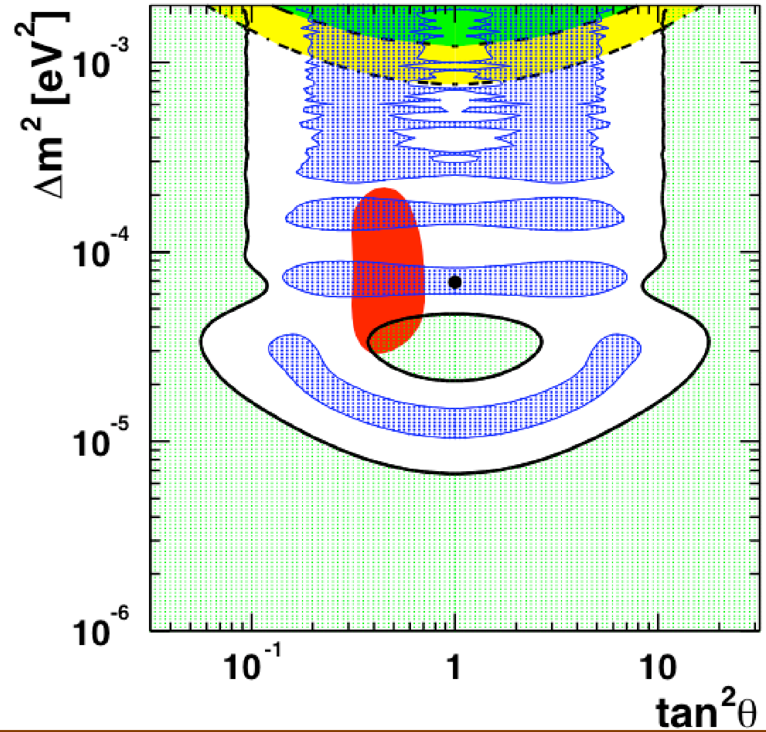
Hitoshi Murayama



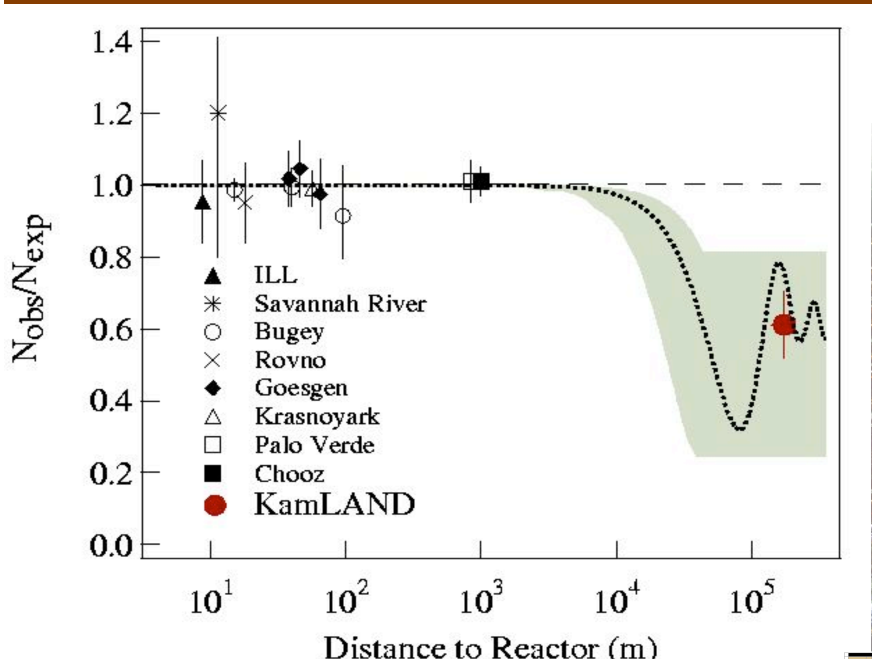
SNO's
Appearance
Experiment

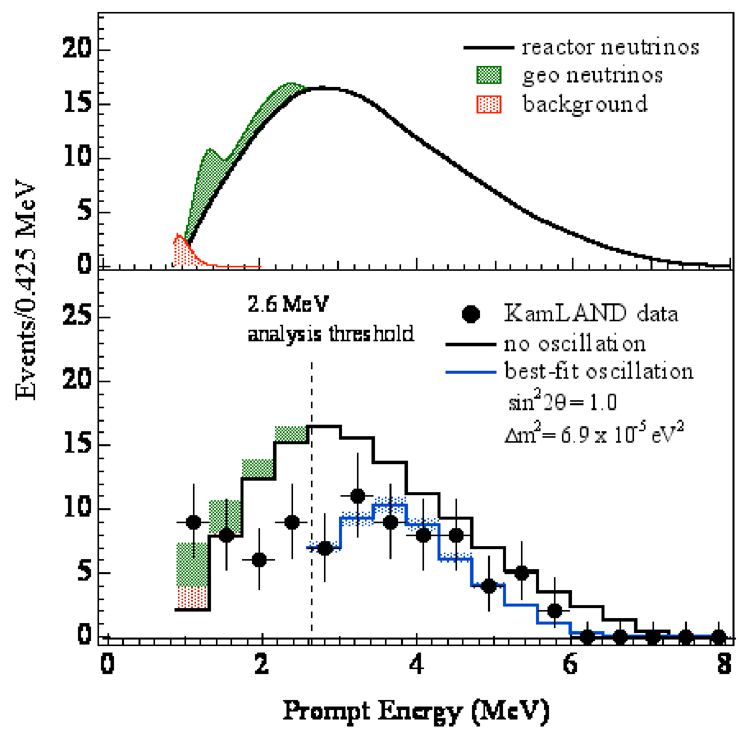


Neutrino Physics - Solar

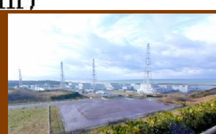


KamLAND - Japan

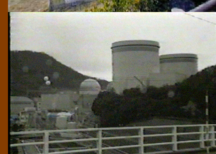




Kashiwazaki



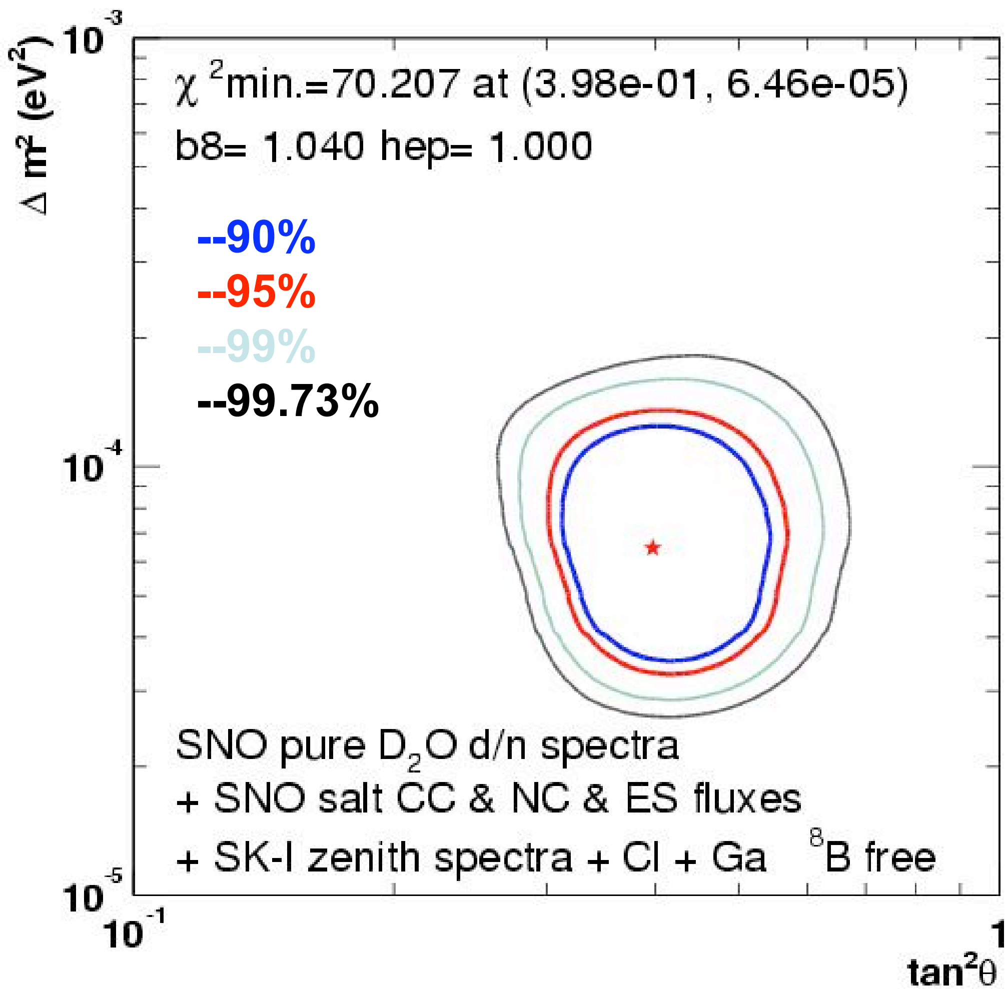
Takahama

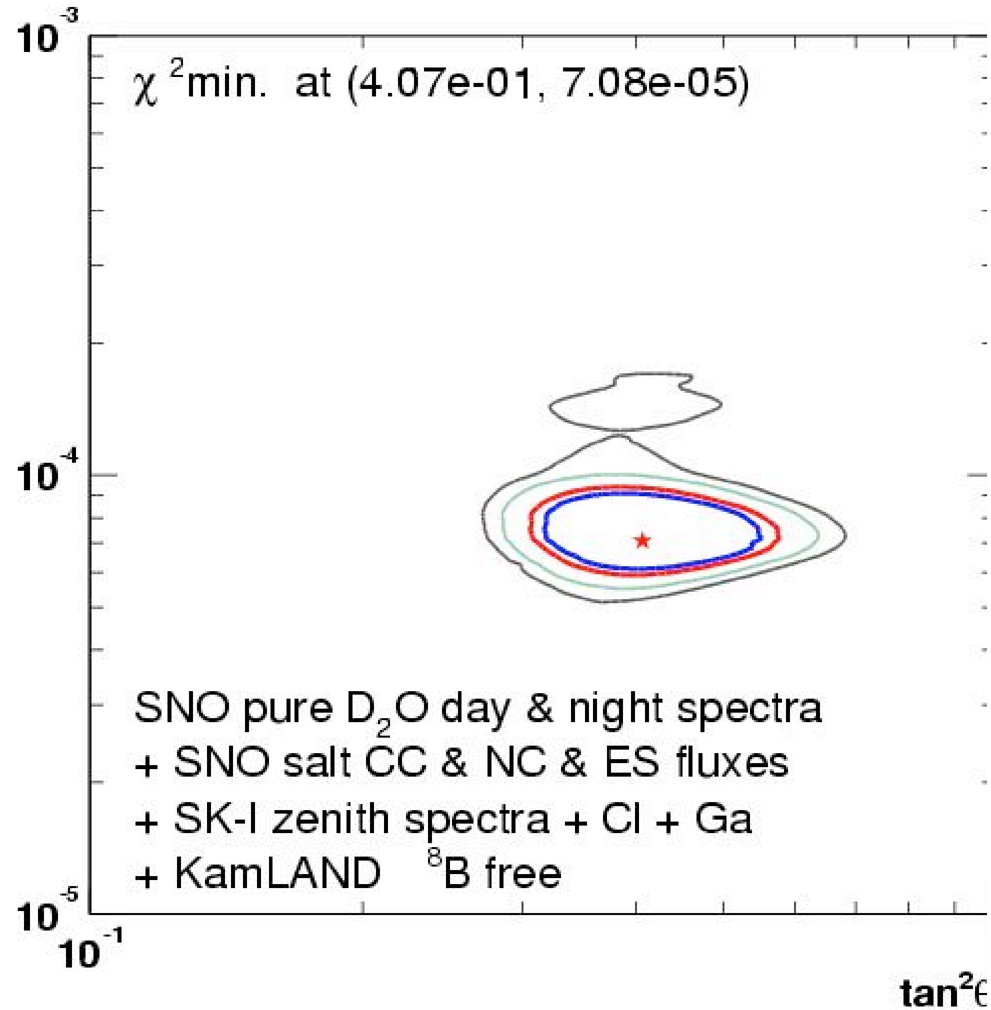


Ohi

Kevin Lesko

Neutrino Physics - Solar



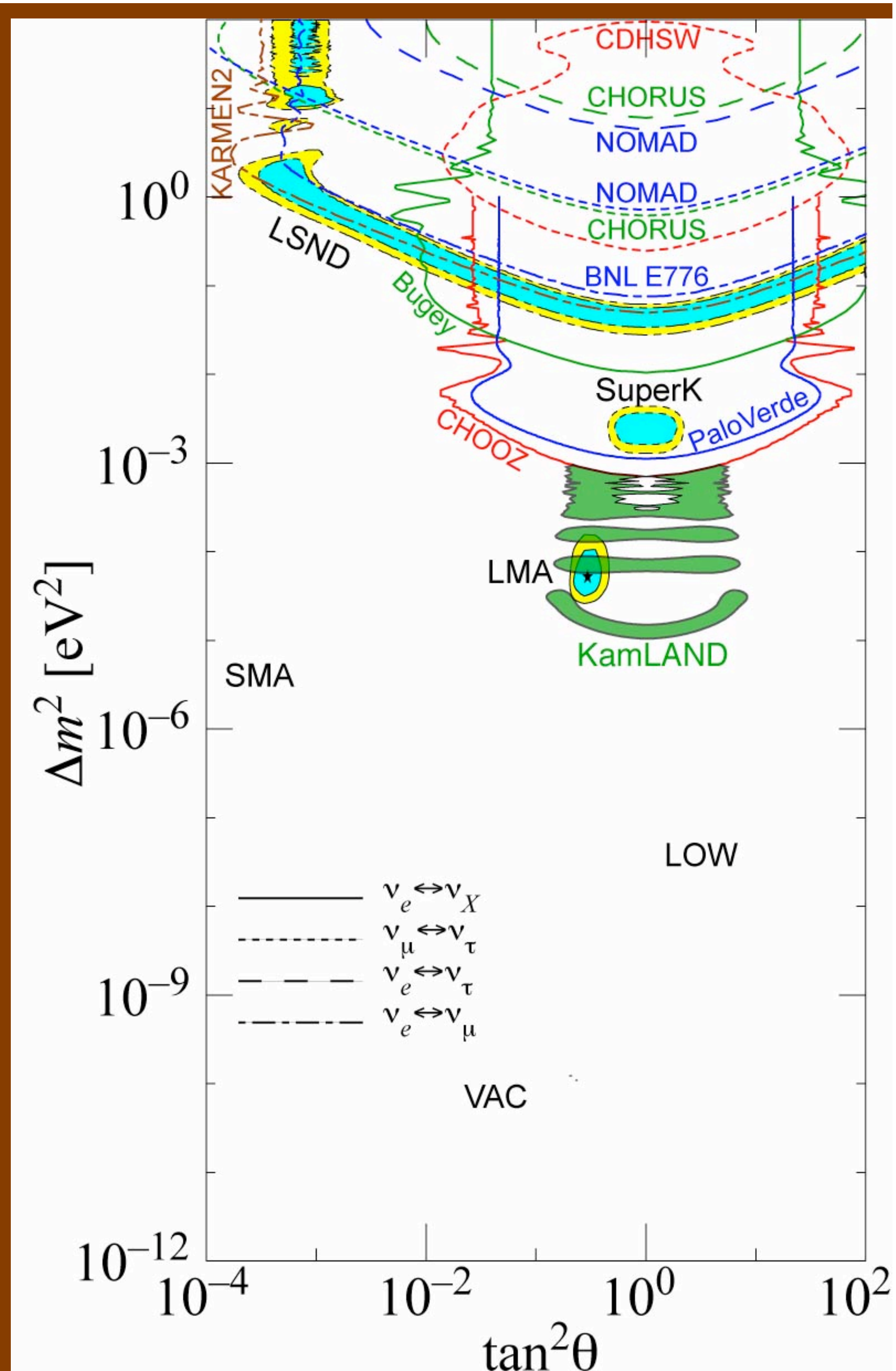


LMA I only at > 99% CL

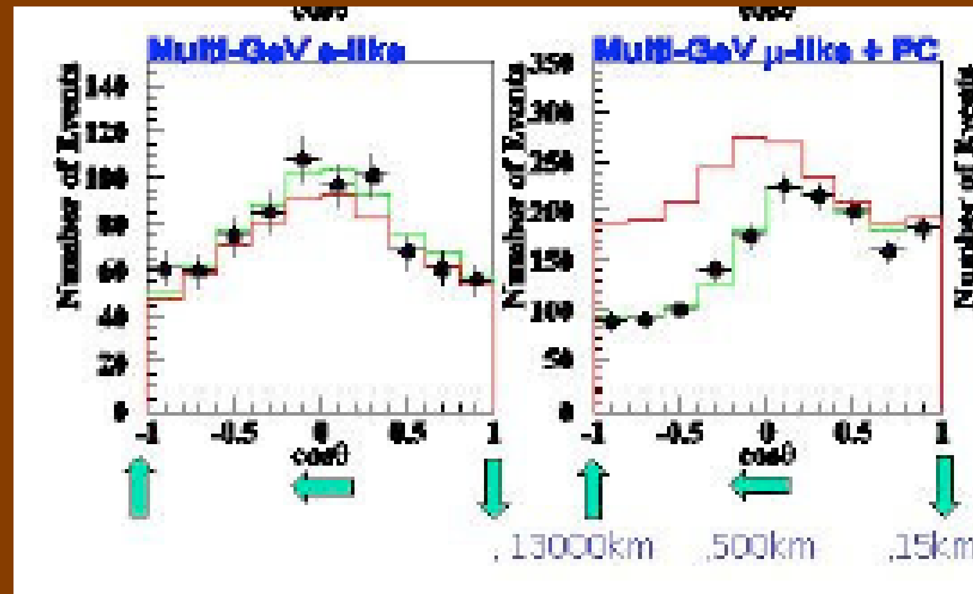
SNO + KamLAND

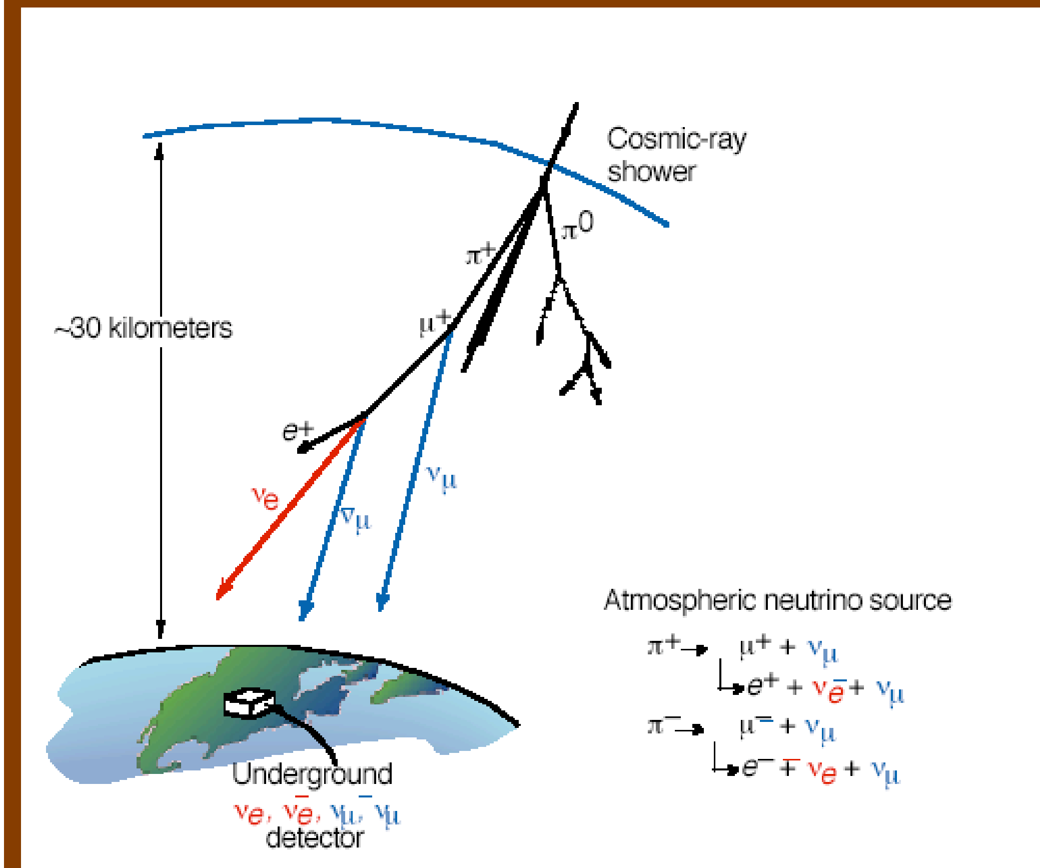
- Reduced ν_e MSW space by 7 orders of magnitude
- No dark side ν_e ($\tan^2\theta<1$) for solar
- LMA (confirmed by KamLAND - assuming CPT)
- Strong Evidence for matter affects
- Massive neutrinos
- Large mixing angles for 2 & small Δm^2

Kevin Lesko



Atmospheric Neutrinos



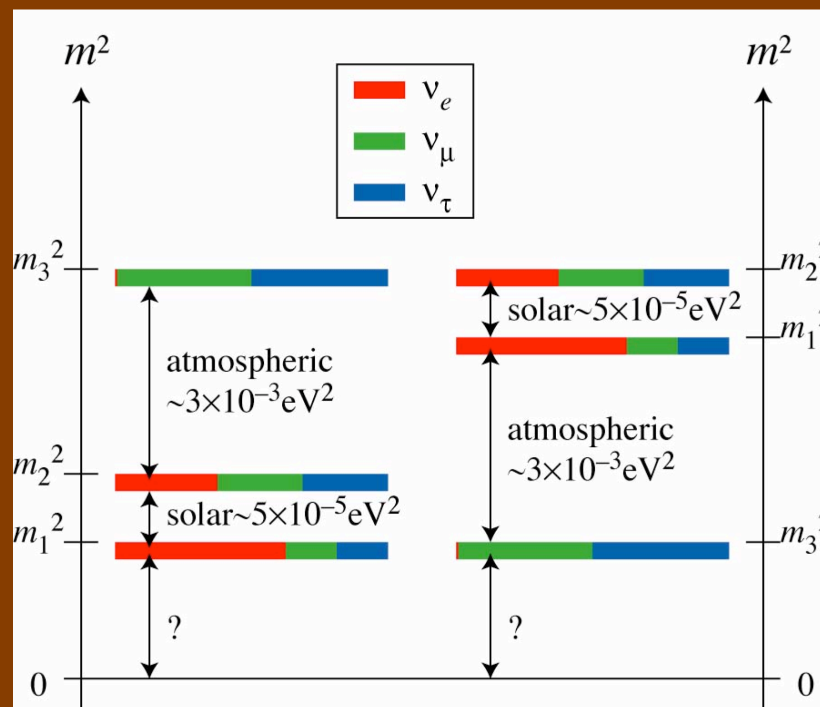


Super-Kamiokanda
>10 □ disappearance expt.

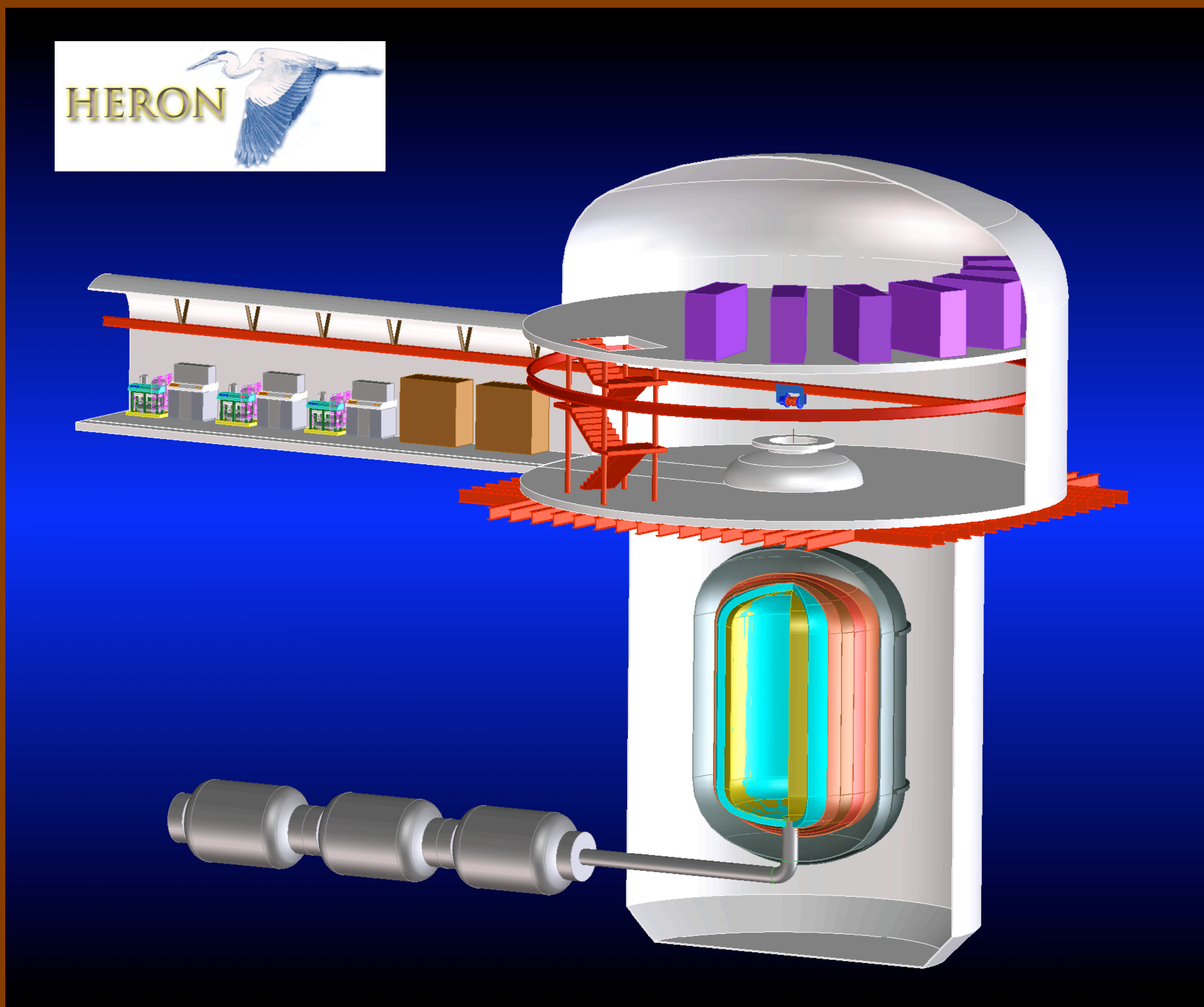
Now being used as Long Baseline Detector as well.

Remaining Questions for Neutrinos

- Neutrino Mass Scale
- MNSP Matrix Elements
  - $\Box_{13}$ - size of angle and possible CP violation
  - $\Box_{12}$ and other elements - Unitarity, number of □s, solar physics
  - Sterile neutrinos
  - Mass hierarchy
  - Verify Oscillations
- Sterile Neutrinos (LSND)?
- CP violation?
- Neutrino Nature
  - Majorana or Dirac

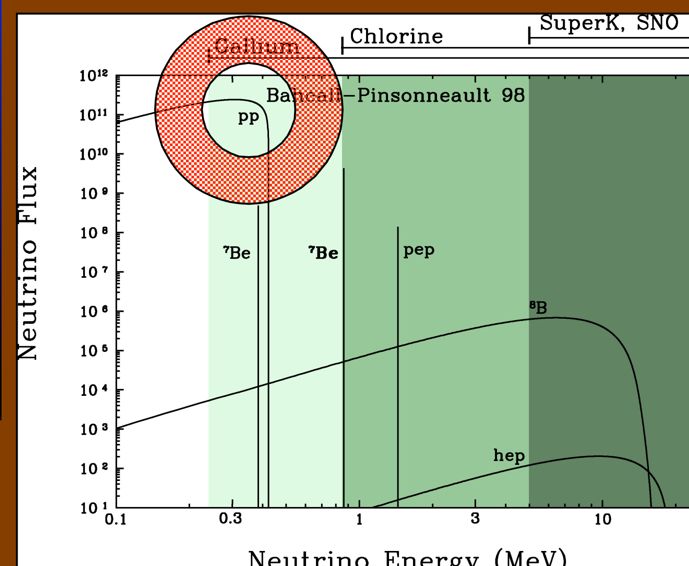


□$_{12}$ experiments



Low energy (pp) neutrino experiment:

- $E_{□} > 50$ keV
- Well known □
- ES, CC expts
- neutrino □$_b$
- solar physics



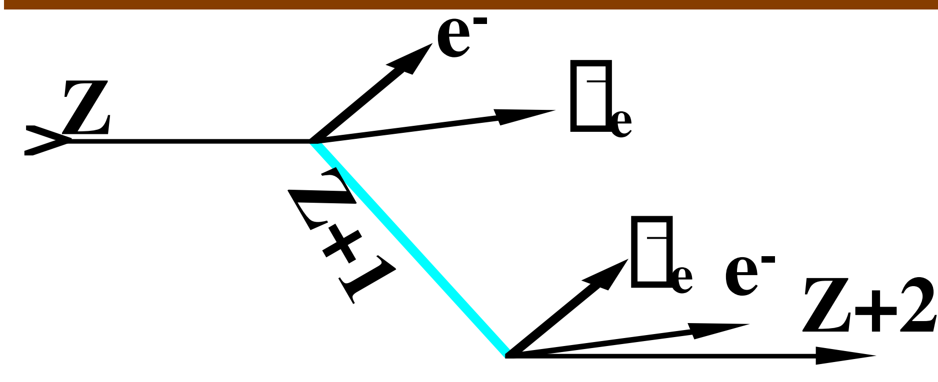
Kevin Lesko

0-ν ββ Decay

- The only known practical approach to discriminate Majorana vs Dirac neutrinos
- Matrix element µ $\langle m_{\nu e}\rangle = \sum_i m_{\nu i} U_{ei}^2$
- Current limit $|\langle m_{\nu e}\rangle| \leq$ about 1eV
- $m_3 \sim (\Delta m^2_{23})^{1/2} \approx 0.05$eV looks a promising goal
- U_{e1}^2 and U_{e2}^2 cannot cancel exactly because the maximal angle excluded by SNO: $U_{e1}^2 - U_{e2}^2 = \cos^2 2\theta_{12} > 0.07$ (1σ)

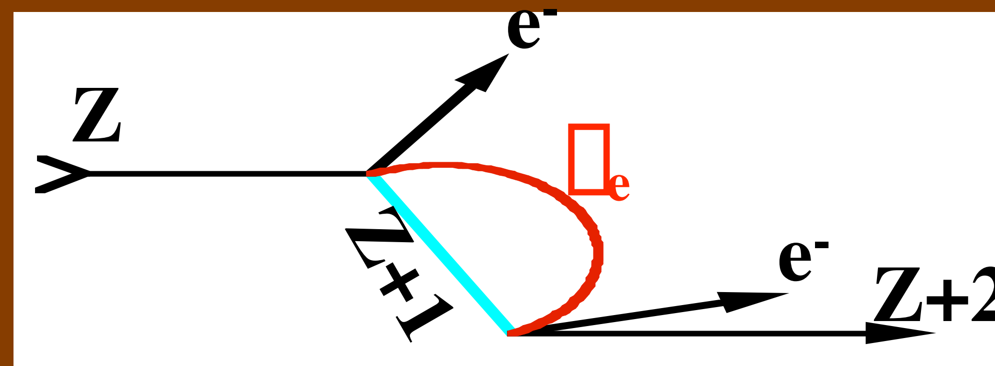
Double Beta Decay

ββ(2ν): Allowed weak decay



$$2n \rightarrow 2p + 2e^{-} + 2\bar{\nu}_e$$

ββ(0ν): requires massive Majorana ν



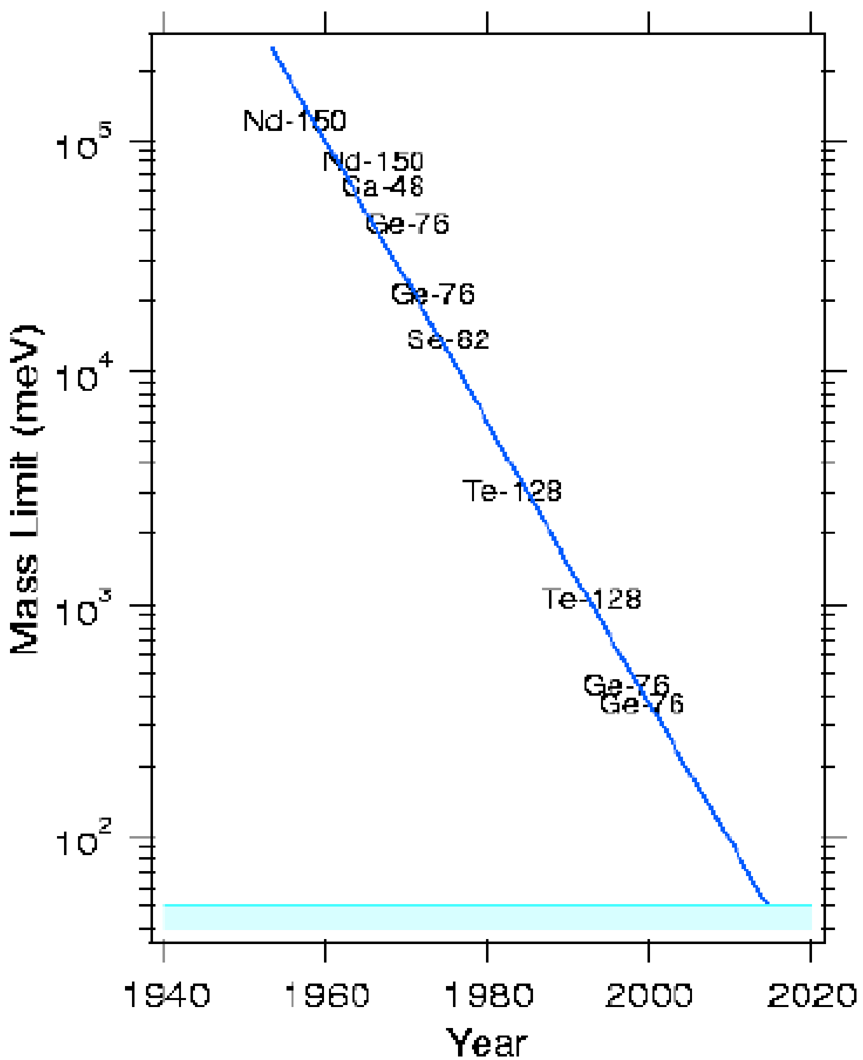
$$n \rightarrow p + e^{-} + \bar{\nu}_e$$

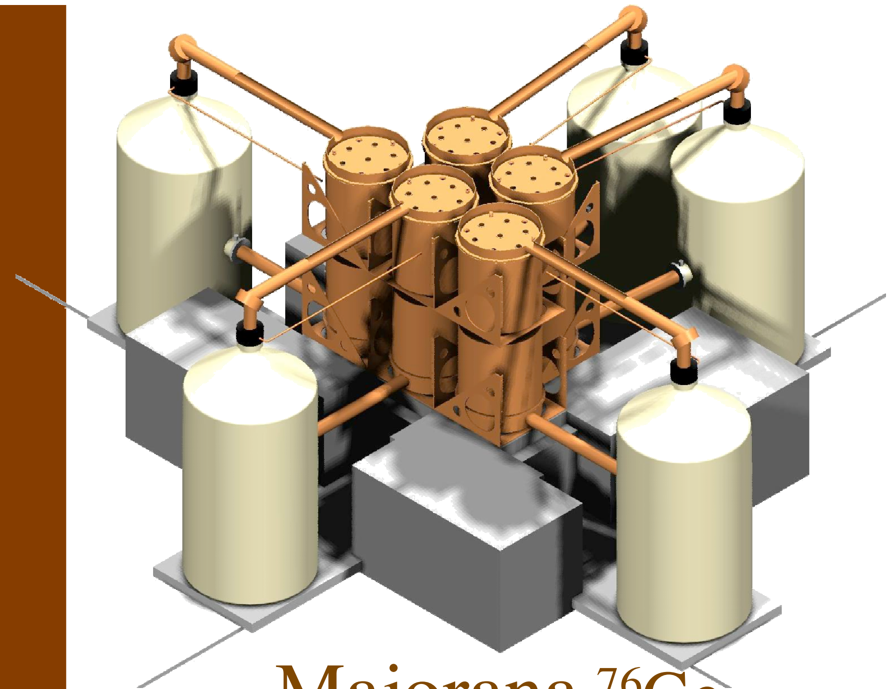
(RH $\bar{\nu}_e$)

(LH ν_e)

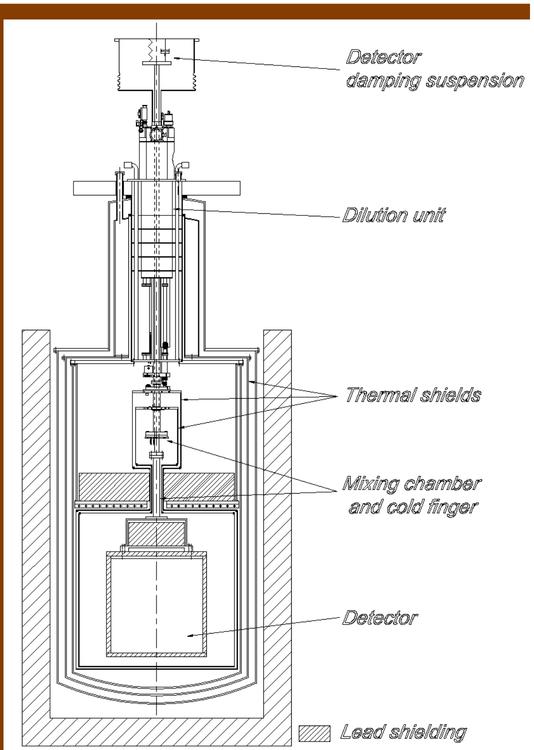
$$\nu_e + n \rightarrow p + e^{-}$$

Double Beta Decay Lifetimes (mass limits) vs Time



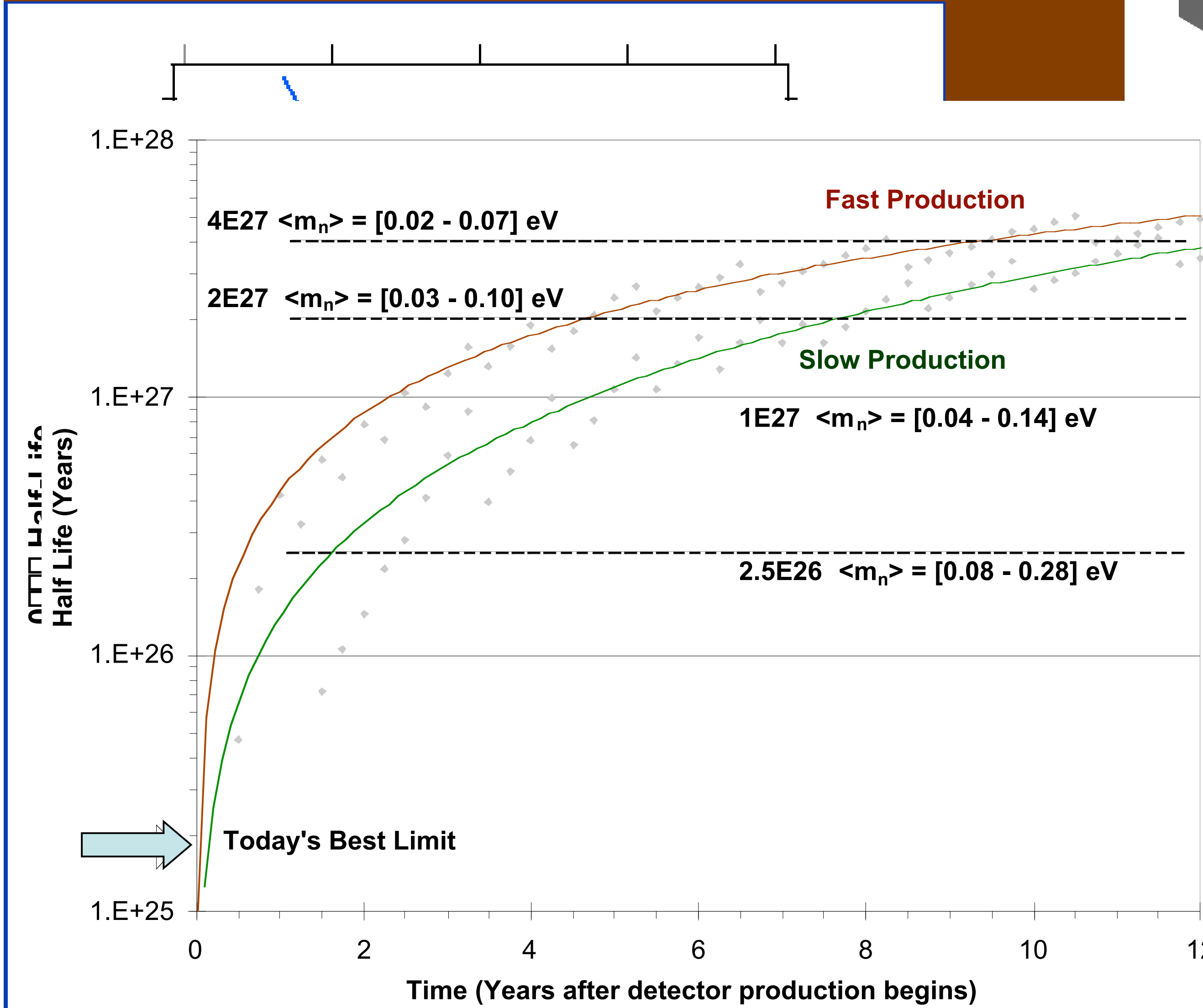


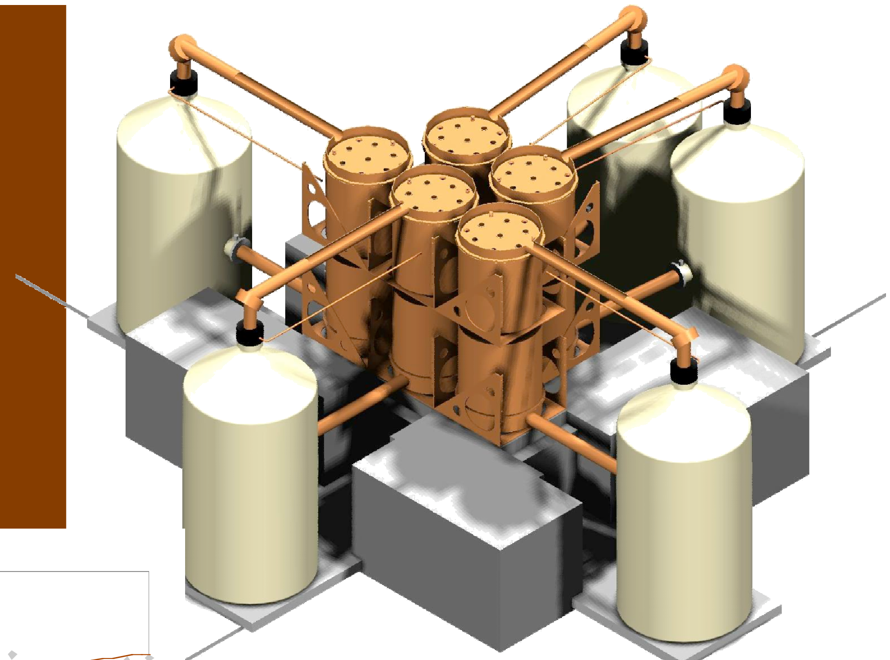
Majorana ^{76}Ge



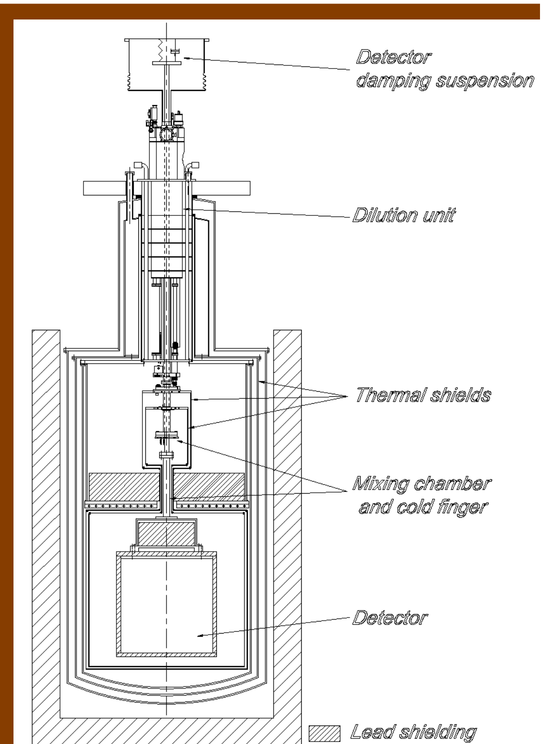
CUORE

Double Beta Decay Lifetimes (mass limits) vs Time





Majorana ^{76}Ge



ORE

Proton Decay

1929: Weyl suggests absolute stability of proton

1938: Stuckelberg and 1949: Wigner postulates existence and conservation of a heavy charged (baryon number) associated with heavy particles

1954: M. Goldhaber (with Reines and Cowan) publishes the first experimental result on proton lifetime inspired by "Continuous Creation" theory

using a liquid scintillator detector

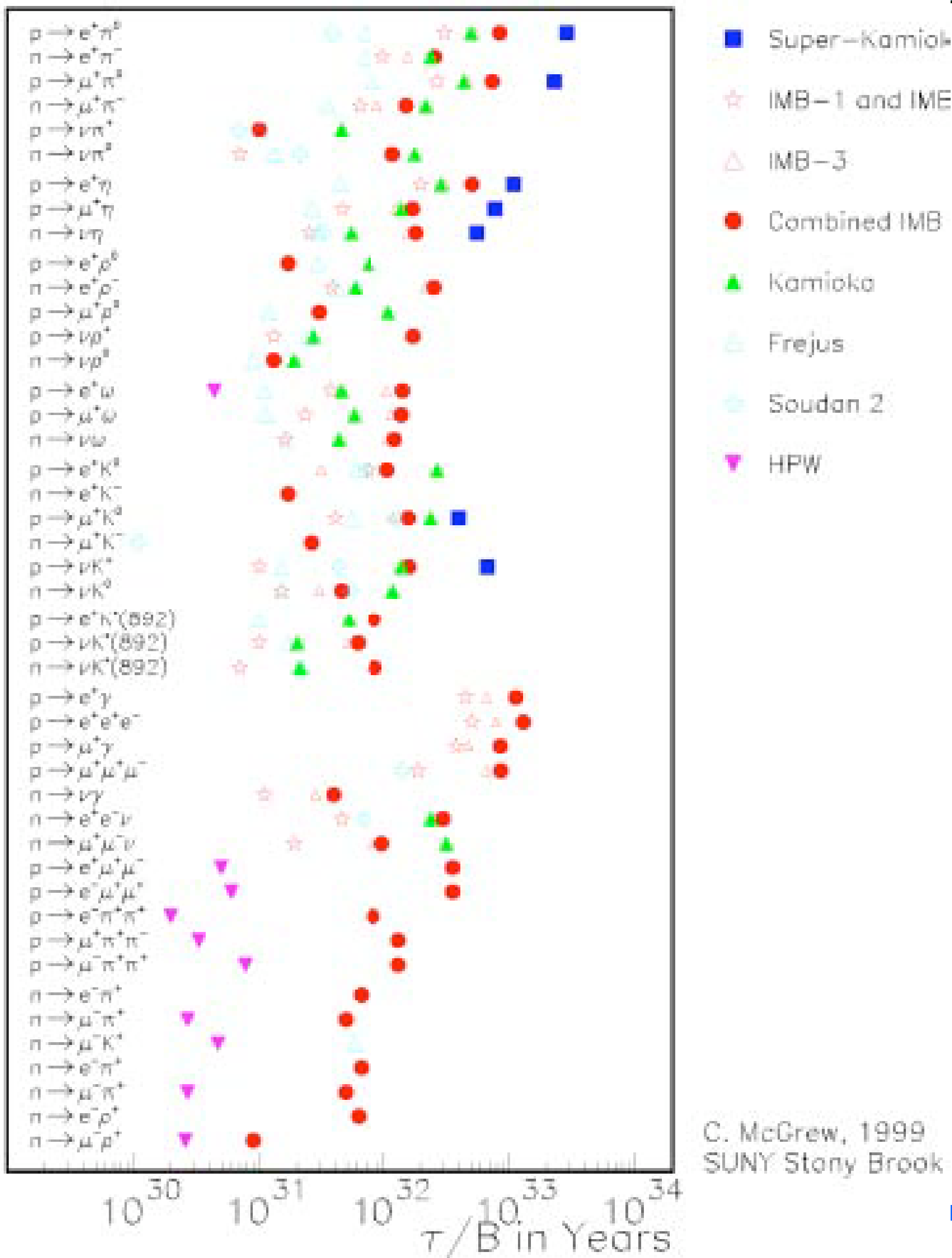
$\tau_p > 10^{21}$ years (free protons)

$\tau_p > 10^{22}$ years (bound nucleons)

Proton Decay

- Stability "questioned" by attempts to unify fundamental forces and particles
- High energy unification of forces in terms of "supersymmetry" suggests a similar scale as the current neutrino masses
- If observed proton-decay provides a key view of physics at short distances, $< 10^{-30}$ cm and of high energies $E > 10^{16}$ GeV
- Current measurements □> 10^{33} years
- Current *guidance* is in the range of $\sim 10^{34}$ to 10^{35} years

Proton Decay

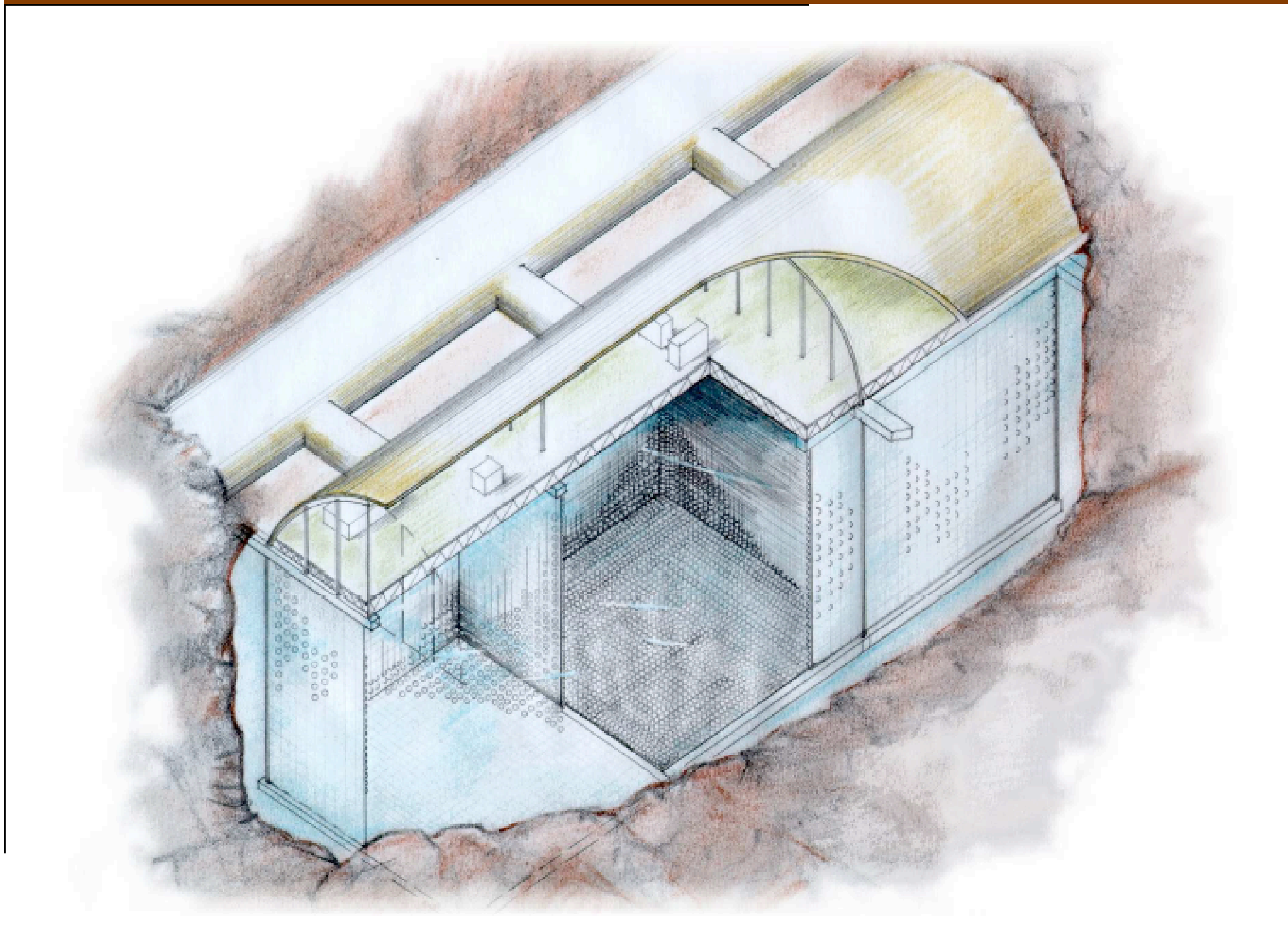


Using Existing Large Volume Detectors can obtain limits O(~ 10^{33} y).

Current Generation Detectors (SNO, KamLAND, Super-K) provide sensitivity to lower energy channels.

New Generation of Detectors indicated.

Proton Decay



UNO

Proton decay

~ 10^{35}a sensitivity

Atmospheric □

huge statistics

Long baseline

BNL or FNAL to NUSEL

Solar □

huge statistics

Supernovae □

see neighboring galaxy

Relic supernovae □

Neutrino astronomy

1/2 Megaton H_2O, 60,000 20” PMTs

Cosmic Accelerators

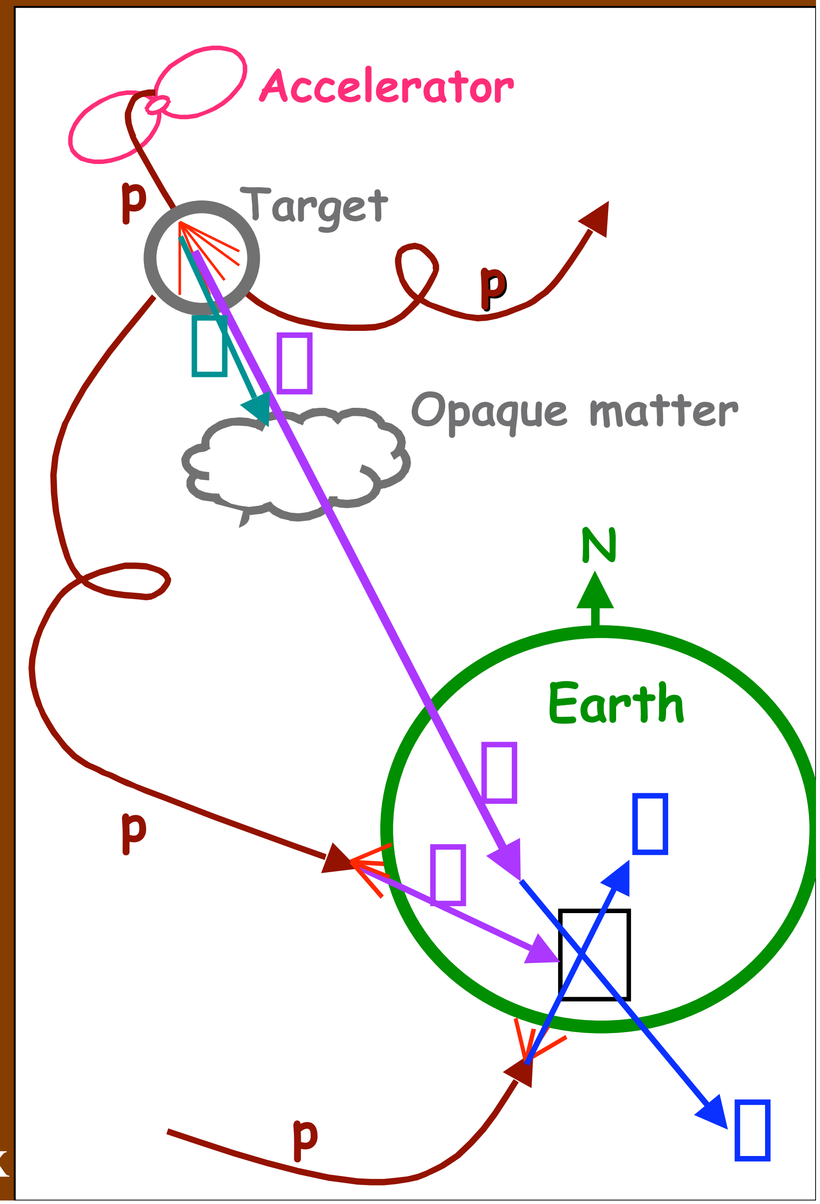
- Goal to understand Cosmic Acceleration and Accelerators - using neutrinos
  - Look for Point-Sources
  - Map out the spectrum
- Matches the Academy’s Scope - edge of Astronomy and Physics
- Requires Experiments on Several Fronts - on the surface and deep underground
- Prospects for Discoveries with this new Spectrum

Cosmic Accelerators

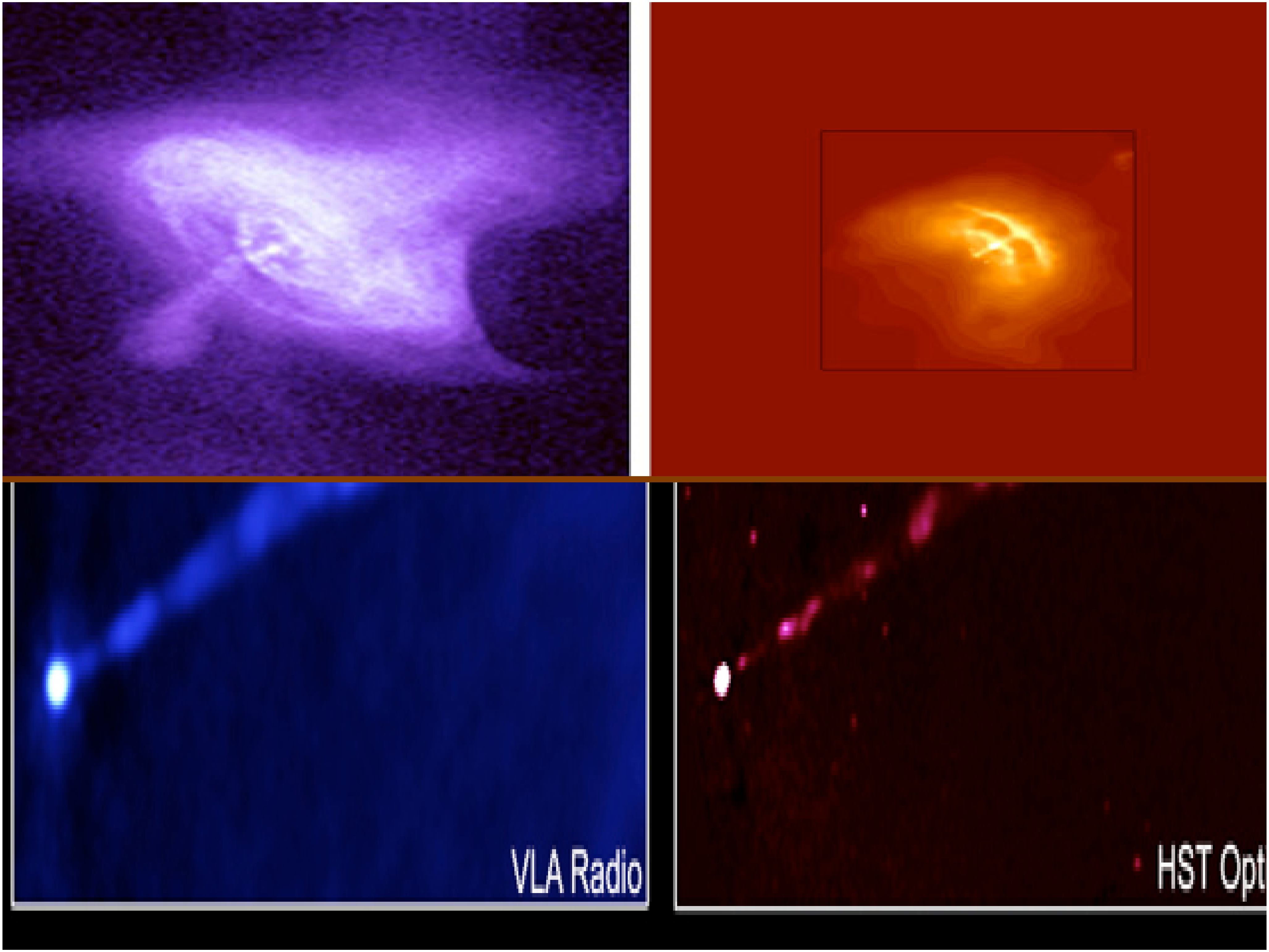
- Stable particles: p, □, □
- Accelerator: magnetic shocks and relativistic blast waves.
- Targets are traditional HEP

$$p + (p,□) \rightarrow □^- + X$$
$$\rightarrow □_□ + □$$
$$\rightarrow □_□ + e + □_e$$

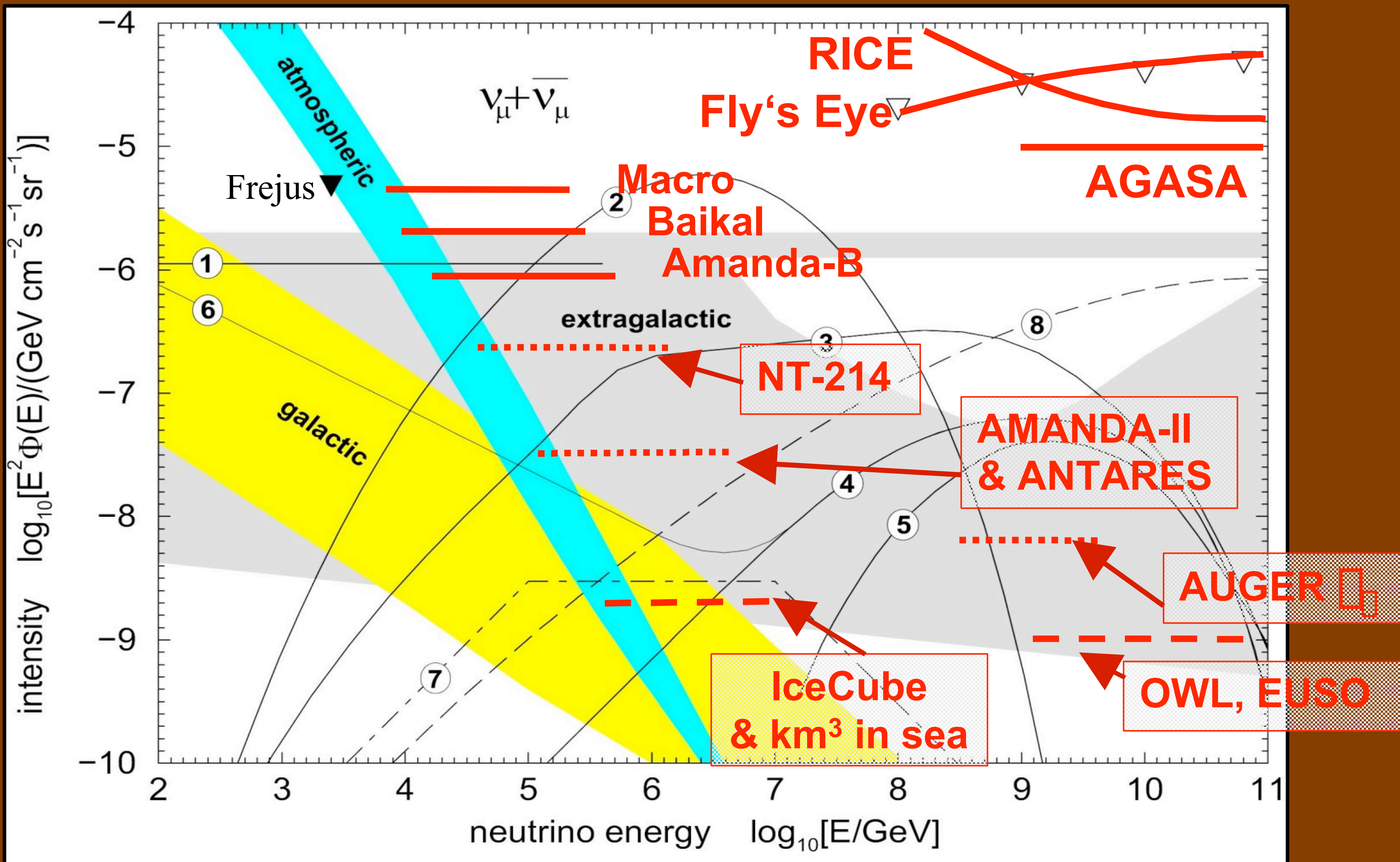
- Astrophysical Sources:
  - -GRB, AGN, Galaxy/Sag-A, SN
  - -GZK (p + CMB □)
- Cosmic Ray Backgrounds:
  - -Atmospheric



Adapted from J. Lamoureux


VLA Radio
HST Opt

Summary of Experimental Results



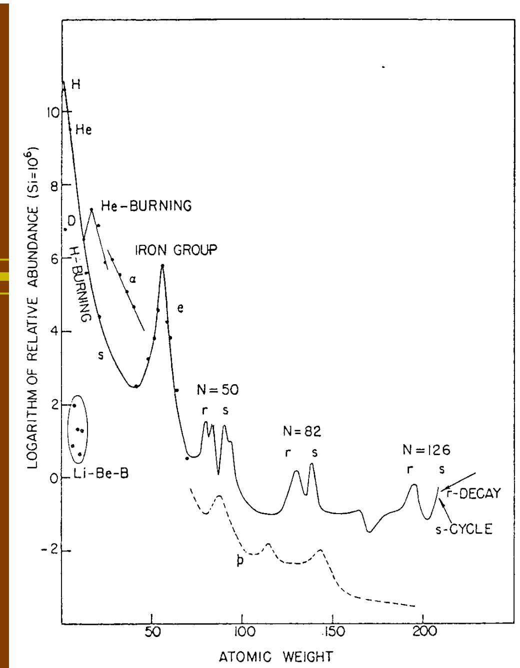
Courtesy: Learned & Mannheim; Spiering

Nuclear Astrophysics/Nucleosynthesis

- Nobel 1983 "for his theoretical and experimental studies of the nuclear reactions of importance in the formation of the chemical elements in the universe"

  Willy Fowler

Nuclear Astrophysics/Nucleosynthesis



- A>60 formation in Supernovae, □ interactions
- Sources of neutrons for s-, r- processes
- Details of Lower Mass Nucleosynthesis
  - pp chain
  - CNO

^{3}He(^{3}He,2p)^{4}He

^{3}He(□,□)^{7}Be

D(^{3}He,p)^{4}He

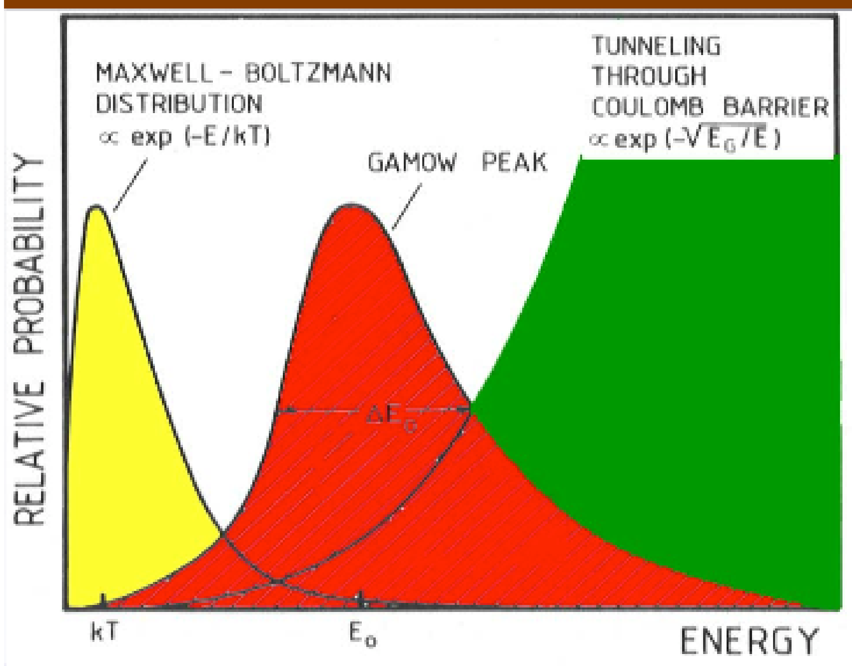
D(p,□)^{3}He

^{7}Be(p,□)^{8}B

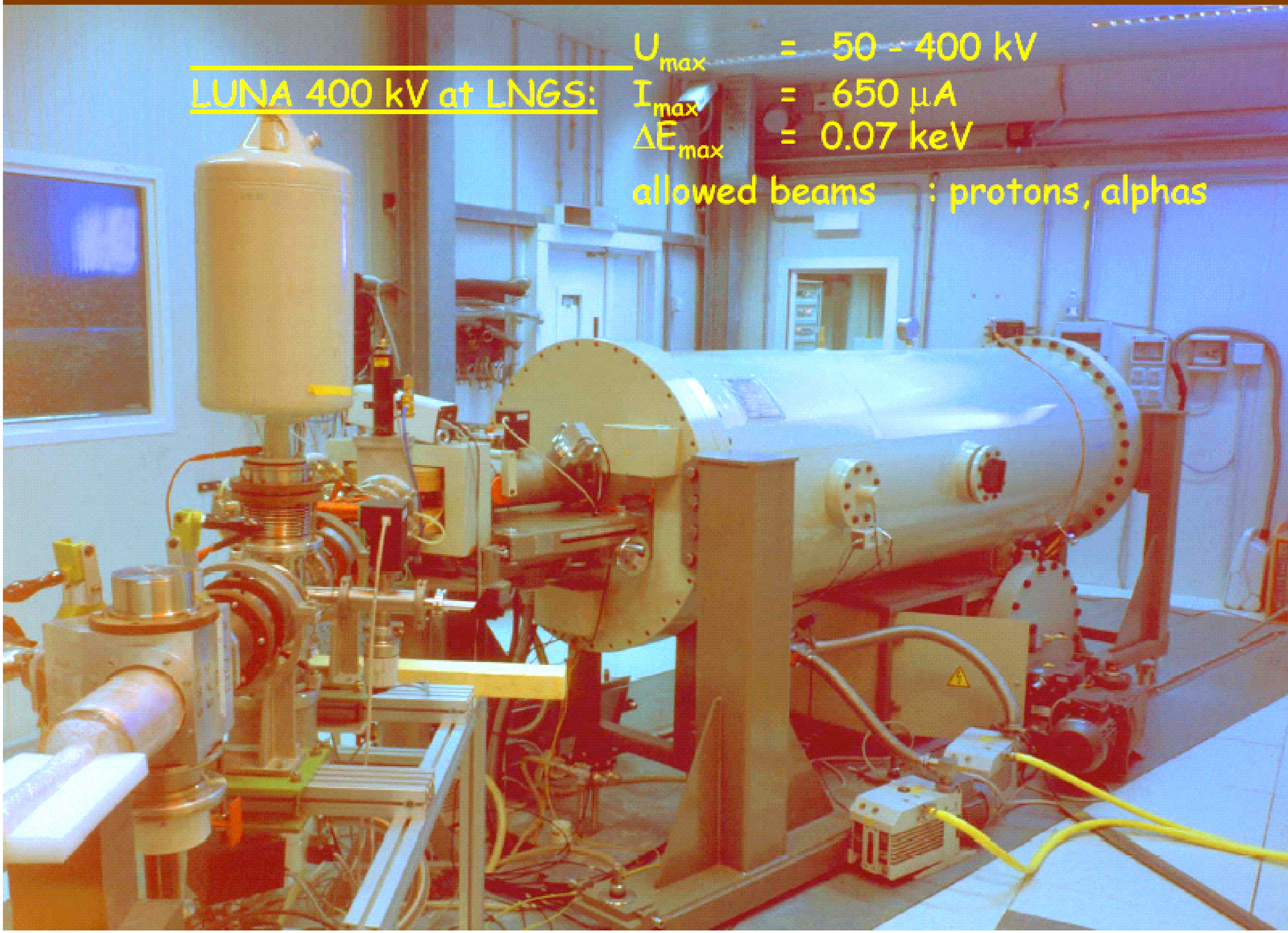
^{14}N(p,□)^{15}O

^{12}C(□,□)^{16}C

…



Nuclear Astrophysics/Nucleosynthesis



Nuclear Astrophysics/Nucleosynthesis

- Bright Prospects for Domestic Program in Nuclear Astrophysics in an Underground Laboratory
  - Complementary energy and current designs to existing facilities
  - Deeper site enables a more ambitious experimental program

Committee Recommendations

1) Birth of the Universe
   measure polarization of CMBR
2) Destiny of the Universe
   Properties of Dark Energy
   LSST, SNAP

3) Unification of Forces from Underground
   Deep Underground Laboratory

4) Basic Laws of Physics from Space
   Constellation-X, LISA

Committee Recommendations

5) Highest Energy Particles

Approach is in place, GLAST, STACEE, VERITAS, ICECube, Auger South

6) Physics Under Extreme Conditions

Bring together the communities to foster field

7) Interagency Initiative on the Physics of the Universe:

Joint planning and implementation of cross-agency projects

Connections to Nuclear Physics

- The recommendations from the National Academy are in excellent agreement with Nuclear Physics Long Range Plan. Specifically - Recommendation #3 supports building an underground lab because

  "*This facility will position the U.S. nuclear science community to lead the next generation of solar and double-beta decay experiments*."
- And even more *nuclear* physics

Two times two makes four seems to me simply a piece of insolence. Two times two makes four is a fop standing with arms akimbo barring your path and spitting. I admit that two times two makes four is an excellent thing, but if we are going to praise everything, two times two makes five is sometimes also a very charming little thing.

Consciousness, for instance, is infinitely superior to two times two makes four.

Fyodor Dostoevsky, *Notes from the Underground*